ACCRI Theme 7

Metrics for comparison of climate impacts from well mixed greenhouse gases and inhomogeneous forcing such as those from UT/LS ozone, contrails and contrail-cirrus

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Executive Summary

Issues of Contention

The United Nations Framework Convention on Climate Change (UNFCC) entered into force in 1994 with the objective for 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. The Kyoto Protocol (1997) set out to reduce emissions of most long-lived greenhouse gases in developed countries to below their 1990 levels. Probably as a result of convenience and simplicity, the chosen metric to compare the climate impact of these greenhouse gases was the 100-year Global Warming Potential (GWP), as calculated by the Intergovernmental Panel of Climate Change Second Assessment Report (IPCC, 1995).

As an integral and growing part of the global economy and transportation sector, aviation has the potential to significantly contribute to changes in the Earth's climate. However, the impact of short-lived species (e.g. nitrogen oxides (NO_x), an ozone precursor which in turn impacts on methane) and effects (e.g. aviation induced contrails) on the climate system depends upon geographical and altitudinal location, season, time of the day and the background meteorology and chemistry during their release (Rogers et al., 2000; Sausen et al., 2005). Such short-lived species therefore require an appropriate metric which takes into consideration these dependencies (Rogers et al., 2002a). For the aviation sector the potential climate impact is dependent upon both long-lived and short-lived emissions and effects, making the choice of a suitable metric that integrates over all effects more difficult.

Gaps

In 1999, the Intergovernmental Panel on Climate Change published a landmark report, 'Aviation and the Global Atmosphere' (IPCC, 1999) which saw the first sectoral examination by the IPCC and estimates of the potential impact resulting from aircraft emissions and their effects. The IPCC (1999) report identified the factors that influence climate. Using radiative forcing as the chosen metric, it found that aviation gives a small but significant climate forcing that is somewhat uncertain in overall magnitude. However, the IPCC (1999) report came out strongly against the use of GWPs in the context of aircraft emissions. In contrast, the most recent IPCC (2007) report presented a range of possible GWPs for aviation NO_x emissions, although not for other aviation effects (Forster et al., 2007).

Due to a pressing need to provide policy-relevant answers to regulatory bodies and industry, many researchers have developed their own metrics to assess the impact of these short-lived species. Unfortunately, these approaches are often scientifically flawed.

The strong statements of IPCC (1999) have certainly affected the landscape of metric design not only for aviation but also for other sectors. With climate change very much on the agenda of international policy and with a need to quantify the climate impact of human emissions, metric evaluation and metric design literature has flourished. Metric design is no longer solely undertaken by physical scientists, but social scientists, economists and industry are developing a plethora of metrics to suit individual needs.

Limitations

There is considerable controversy about the application of emission metrics to assess the effect of aviation non-CO_2 emissions. IPCC (1999) stated that the global warming potential "has flaws that make its use questionable for aviation emissions" and that "there is a basic impossibility of defining a GWP for aircraft NO_x". Wit et al. (2005) echo these sentiments, concluding that "GWPs are not a useful tool for calculating the complete suite of aircraft effects". An undesirable side effect of the negative stance is that it has led some policymakers and other groups to apply a Radiative Forcing Index (RFI) as if it is some kind of alternative to the GWP (see Forster et al., 2006).

It is certainly true that major caveats are required in the presentation and application of any currently proposed emissions metric. However, it needs to be clearly recognised that some difficulties are not a function of the metric design but are due to more fundamental limitations of our understanding of atmospheric processes. One example is the impact of persistent contrails on cirrus clouds; these certainly do preclude confident evaluation of values of GWPs, but the problem is much deeper than the evaluation of metrics – *any* attempt to quantify their impact, using even the most sophisticated climate models, would face similar limitations. Other limitations are more structural, such as the problem in using global-mean values for NO_x emissions, when compensation between negative forcings at a global level may not apply at the hemispheric level.

Priorities

A list of recommended priorities for tackling the outstanding issues related to the development and implementation of an appropriate metric for determining aviation's climate impact are given below: All of the tasks listed are achievable and will significantly improve our understanding of climate impacts whilst reducing scientific uncertainty

- Understand that metric choice is not solely a science issue –policy comes into play. Therefore a range of people from different disciplines, including policy makers and scientists need to be involved in metric choice.
- Assessment of the literature on alternative approaches to the use of GWPs as a suitable metric of climate change.
- Diagnosis of the variation of the climate sensitivity parameter with forcing agent.
- A study of climate impacts and their robust beyond global mean temperature change, with particular emphasis on the local response

- Assessment of the potential range of impacts diagnosed using a spectrum of metrics and timescales.
- Appropriateness of cancelling negative and positive climate effects - improved understanding as to whether multiple climate effects can be combined and how global cancellation affects local responses.
- Appropriateness of pulsed or sustained emissions of realistic scenarios - improved understanding of how scenario choice leads to different implications of aviation impact.
- Improved understanding of how background climate change and atmospheric conditions affect forcing, climate impact and metric choice.

Recommendations for Research Needs

- Improved description of NO_x and NO_y chemistry, sources and sinks particularly related to the chemistry of the UTLS region and potential anthropogenic impacts.
- Improved model prediction of dynamical climate feedback processes throughout the lower atmosphere.
- Investigations of how regional localised emissions affect climate both locally and globally
- Study of the processes and radiative effects of contrails and aircraft induced cirrus.
- Development of methods for ascertaining and forecasting supersaturation for use in cloud and contrail prediction
- Model-model intercomparison and model-measurement intercomparison - understanding of the interaction between ozone and methane.
- Impact of a pulse emission of NO_x emitted under different atmospheric conditions and seasons.
- Quantification of the full effect of aviation under potential operational and technical procedures.
- Long-term observational capability for integrated monitoring of climate gases and clouds.
- Coniuted development of social and economic metric approach , with an acknowledgement of their limitations

‘Practical’ Application of Current Knowledge and Capability

In general, we recommend continued science studies to reduce uncertainties where achievable, and the use of simple metrics. We recommend quoting ranges for a number of metrics, as different metrics give different indications of importance. This also prevents metrics being deliberately chosen to advocate particular policy choices. Development of our understanding of the atmosphere and computational power should eventually enable sophisticated coupled climate models to be used to explore metrics of aviations impact.

Specifically, our recommended approaches involve simple metrics only (GWP and GTP) and includes all forcing factors that are relatively well quantified (currently excluding the role of aviation induced cirrus). Since likely future policy will be directed towards reductions by a particular target date, we recommend the adoption of ASGTP(H), limited probably to a target date around 2060. Further, with present knowledge we recommend only applying these metrics at the globally-averaged emission level, i.e. not applying different GWPs to emissions from different regions/heights/seasons etc.

1. Introduction and Background

The Earth's climate is warming and human activity is *very likely* (90% certain) to be responsible for the warming observed over recent decades (IPCC WG1, 2007). The largest contribution to both past climate change and expected future climate results from emissions of long-lived greenhouse gases. Due to their long life-time in the atmosphere (greater than 10 years) the climate effects of these emissions are not location specific and are readily comparable using simple metrics (Forster et al., 2007).

The United Nations Framework Convention on Climate Change (UNFCC) entered into force in 1994 with the objective for 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. The Kyoto Protocol (1997) set out to reduce emissions of most long-lived greenhouse gases in developed countries to below their 1990 levels. As a clear climate-change target was never defined, the Kyoto protocol aimed simply to limit emissions of several greenhouse gases: carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); hydrofluorocarbons (HFCs); perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Probably as a result of convenience and simplicity, the chosen metric to compare the climate impact of these greenhouse gases was the 100-year Global Warming Potential (GWP), as calculated by the Intergovernmental Panel of Climate Change Second Assessment Report (IPCC, 1995). In recent years a more targeted approach has been developed to directly address the issue of 'dangerous climate change'. A 2005 UK initiative (Avoiding Dangerous climate Change, 2005) suggested that a globally average temperature rise of 2K or more from pre-industrial times would be 'dangerous' - largely because of the possibility of destabilising high latitude ice caps (especially Greenland) and permafrost melt. This would cause rapid sea-level rise and other positive feedbacks. A similar description of temperature thresholds beyond which climate change becomes 'dangerous' has recently become internationally recognised in European Union climate change policy. The IPCC (2007) WGIII Fourth Assessment report (AR4) also analysed mitigation polices to keep global mean temperatures below certain target thresholds and such an approach is likely to feature in any agreement made at the UN Climate Change conference in Bali at the beginning of December 2007.

Predicting future warming depends both on climate model behaviours (such as climate sensitivity) and future emission scenarios – both are uncertain. Nevertheless, based on standard future emission scenarios we expect 'dangerous' warming (a globally averaged temperature rise of 2K or more from pre-industrial times) to be reached before the end of this century (Figure 1). Potential impacts of these target thresholds are shown in Figure 1.

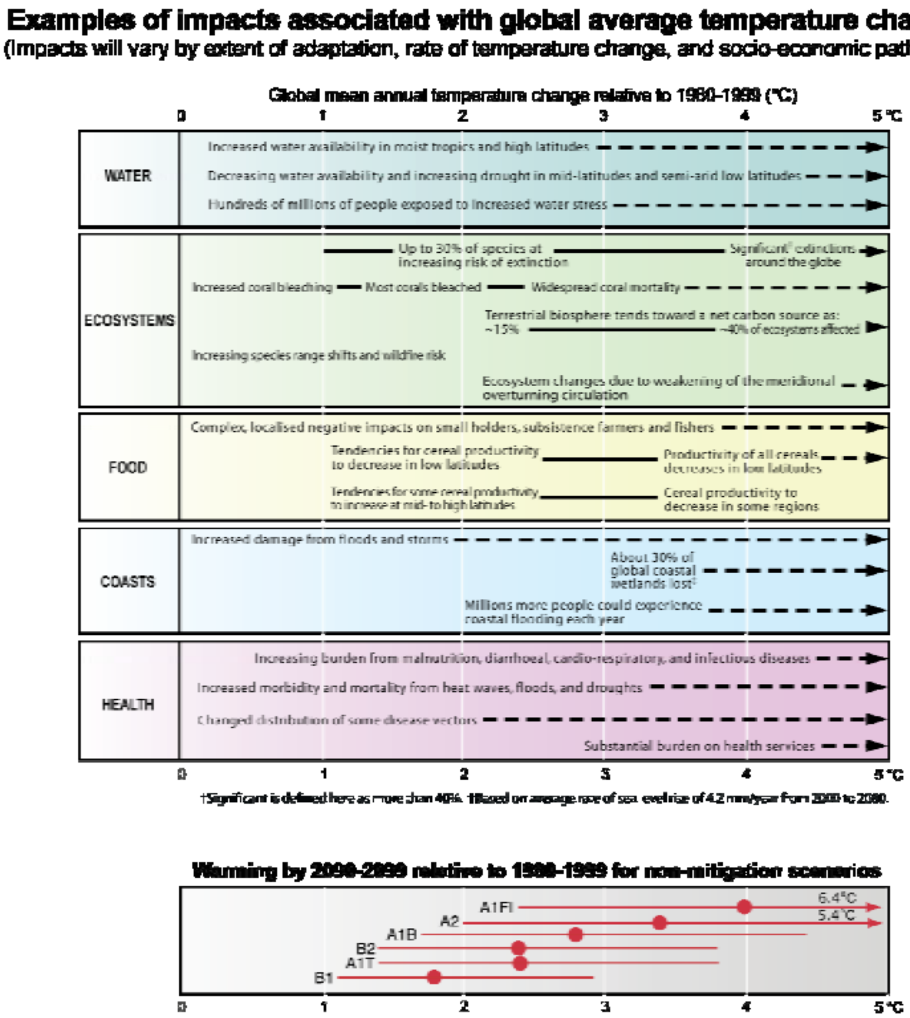

Figure SPM.7. Examples of impacts associated with projected global average surface warming. Upper panel: Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric CO_2 where relevant) associated with different amounts of increase in global average surface temperature in the 21st century. The black lines link impacts; broken-line arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left hand side of text indicates the approximate level of warming that is associated with the onset of a given impact. Quantitative entries for water scarcity and flooding represent the additional impacts of climate change relative to the conditions projected across the range of SRES scenarios A1FI, A2, B1 and B2. Adaptation to climate change is not included in these estimations. Confidence levels for all statements are *high*. Lower panel: Dots and bars indicate the best estimate and *likely* ranges of warming assessed for the six SRES marker scenarios for 2090-2099 relative to 1980-1999. {Figure 3.5}

Figure 1. Taken from IPCC AR4 Synthesis report, showing how climate impacts relate to global mean temperature change.

Interest in the effects of emissions from subsonic aircraft grew in the late 1980s and early 1990s (Schumann, 1990). This interest stemmed from an increased appreciation that the upper troposphere and lower stratosphere, the cruise altitude of subsonic aircraft, is a sensitive region of the atmosphere for both chemistry and climate changes. Initially the attention was placed upon the effects of NO_x emission from aviation on tropospheric O_3 production (e.g. the EU AERONOX and the US SASS projects, Schumann 1997; Friedl *et al*., 1997). More recently the potential climate impact of other effects such as those of condensation clouds (contrails) and cirrus have been the focus of intensive investigation (e.g. Sausen et al., 2005).

The aviation sector has continued to grow strongly over the 1990s and early 2000s, despite events such as the Gulf War, 9-11 and SARS. As an integral and growing part of the global economy and transportation sector, aviation has the potential to significantly contribute to changes in the Earth's climate. However, the impact of short-lived species (e.g. nitrogen oxides (NO_x), an ozone precursor which in turn impacts on methane) and effects (e.g. aviation induced contrails) on the climate system depends upon geographical and altitudinal location, season, time of the day and the background meteorology and chemistry during their release (Rogers et al., 2000; Sausen et al., 2005). Such short-lived species therefore require an appropriate metric which takes into consideration these dependencies (Rogers et al., 2002a). For the aviation sector the potential climate impact is dependent upon both long-lived and short-lived emissions and effects, making the choice of a suitable metric that integrates over all effects more difficult.

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Concern over the future effects of aviation on climate remain the subject of debate both in the science and policy arena. As a result, scientific and technical assessment work has continued since the publication of the IPCC (1999) report and some of this has been reported and synthesized in the recent IPCC AR4 *2007) by its Working Groups I (science) and III (adaptation and mitigation). WGI and WGIII addressed disparate aspects of aviation, although there are important linkages, especially associated with metrics. In the WGI report, the aspects that have received the most attention in atmospheric science, namely contrails and aviation-induced cloudiness were considered in some detail. The WGIII report focussed its attention on the possibilities of mitigating aviation impacts from a technological standpoint, and considered other aspects such as policies and measures that might be introduced.

This SSWP relies heavily on published literature, together with state-of-the-art research from appropriate academic initiatives (e.g. UK-OMEGA, EU-QUANTIFY, EU-

ATTICA, USA-PARTNER) in order discuss the metric problem in detail, assessing current levels of understanding, gaps in our knowledge and future possibilities.

2. Review

Before reviewing the literature on metrics it is important to briefly assess our overall understanding of aviation's role in climate change. It is also important to introduce past and future predicted trends in aviation traffic and discuss flight locations. As all of these features influence metric discussion.

2.1. Current state of science

2.1.1. Air travel – its emissions and its trends

Aviation is a fundamental part of business and commerce, and as the globalisation of industry and commerce has increased so aviation has undergone spectacular growth, outstripping GDP. There are many forecasts available for the future growth of civil aviation traffic. Aerospace companies, aircraft manufacturers and airlines provide forecasts for business projections. The UK Department for Business Enterprise and Regulatory Reform provides its own market forecasts in order to inform UK government policy. Most aviation growth forecasts rely upon assessments of global economic trends, due to the close linkage between global GDP growth and aviation traffic growth. Passenger traffic is expected to average around 5.3% annual growth over the coming years (see Figure 2). The increased global capacity in aviation will be provided by around 14,000 new aircraft between 1999 and 2018. Approximately half of this demand is expected to be derived from the replacement of existing aircraft retired from the fleet, with the other half generated by anticipated traffic growth. The environmental performance of civil aviation maintains a growing profile in social awareness and imposes pressures on the aviation industry to which it will need to respond.

Members of the European Regions Airline Association (ERA) have recorded significant growth for the first six months of 2007. Scheduled passenger traffic increased by 7.7% compared to the first half of 2006 with scheduled passenger kilometers increasing by 9.7% on the same period last year. Capacity levels for ERA member airlines have also been growing with seat numbers up 5.3% and available seat kilometers up 7.8% in the first six months of 2007 when compared to the same period in 2006.

For reasons of economy of operation, range and market demand, there has been a constant drive towards more fuel-efficient aircraft. Following the introduction of jet aircraft into the civil aviation fleet, approximately 40 years ago, fuel consumption per passenger-km has been reduced by approximately 70%. The most significant gains have been achieved through engine improvements and further improvements in efficiency are forecast to continue into the future.

Early research on aircraft emissions was focused primarily on improvements in the combustor technology required to meet the emerging landing/takeoff regulations. Today, the focus has widened beyond the locality of the airport to include emissions at higher altitude. Improvements to all aircraft components are required to meet the environmental concerns.

Gas turbine exhausts contain concentrations of CO_2, water vapour (H_2O), NO_x, sulphur compounds (SO_x, originating from sulphur in the fuel) and trace amounts of numerous other chemical species. In general, emissions of NO_x, CO, HCs and particles are relevant to local air quality issues whilst CO_2, H_2O, NO_x, SO_x and particles are of particular interest for climate change. Table 2 outlines the distance flown, fuel usage and emission products from civil and military aviation for 2002, as provided by the AERO2K database.

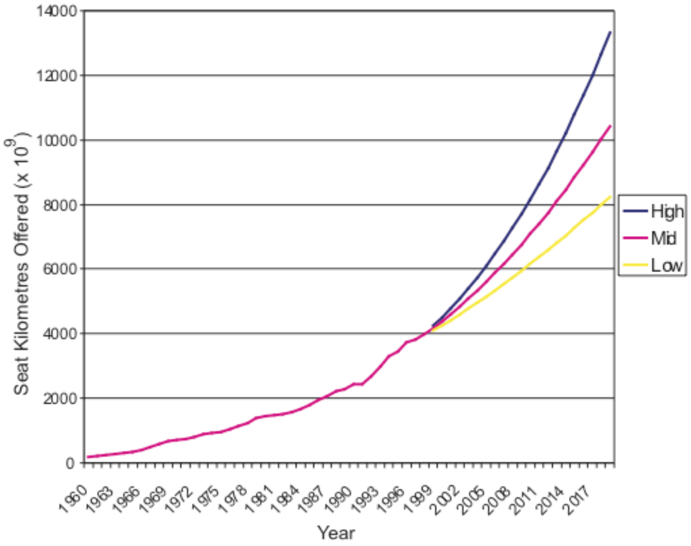

Figure 2. Aviation growth in terms of global SKO (seat kilometres offered) between 1960 and 2020 (source: UK. DTI data) – as in Rogers et al., 2002a.

	Distance Flown	Fuel Used	CO_2 Produced	H_2O Produced	CO Produced	NO_x Produced	HC Produced	Soot Produced	Particles Produced
	Nautical miles x 10^{-9})	(Tg)	(Tg)	(Tg)	(Tg)	(Tg)	(Tg)	(Tg)	(X 10^{-25})
Civil Aviation	17.9	156	492	193	.507	2.06	.063	.0039	4.03
Military Aviation	n/a	19.5	61.5	24.1	.627	.178	.064	n/a	n/a
AERO2K Total	n/a	176	553	217	1.13	2.24	0.127	n/a	n/a

Table 1: Emission for AERO2K dataset in 2002 (Eyers et al,. 2004).

Past and future aviation growth significantly influences the metric discussion. For example past rapid growth in aviation is responsible for the currently large non-CO_2 forcings from aviation, compared to the CO_2 forcing, which rises more slowly. Growth in the future will also affect choice of metric

2.1.2. Aviation's climate impact

This assessment largely draws on the IPCC AR4 assessment report (Forster et al., 2007) which in turn was largely based on Sausen et al. (2005). Together these works provide a valuable overview of the significant developments achieved following the IPCC (1999) report.

Aviation emits gases and particles that in turn affect the climate by changing the atmospheric abundance of constituents and/or cloudiness. These effects are typically assessed by calculating the radiative forcing (RF, with units of Wm^{-2}) imbalance at the tropopause (see Forster et al., 2007 for details). These effects arise from:

- emission of CO_2, which has a warming effect (positive RF);
- emission of NO_x, which results in the production of tropospheric O_3 (positive RF) and the reduction of ambient CH_4, a cooling effect (negative RF);
- direct emissions of H_2O (positive RF);
- the formation of line-shaped contrails (positive RF);
- the increase of cirrus clouds by spreading contrails (positive RF);
- the emission of sulphate particles (negative RF) and;
- the emission of soot particles (positive RF).
- the indirect effects of aviation aerosols on background cloudiness (unknown RF)

and are typically quantified in terms of a global average RF -see Figure 3. Each mechanism can be given a level of scientific understanding which incorporates both the evidence for the mechanism's existence and the consensus on the degree to which individual studies agree. It is important to note however that these mechanisms may each have different geographical distributions and timescales, and that, with the exception of CO_2, the impact is determined using the steady state change in concentrations resulting from 2005 emissions. Another necessary consideration when designing metrics is how radiative forcing translates into surface temperature change and/or other impacts. For example, studies have indicated that contrails may have a direct local impact on surface temperatures over the US including the diurnal temperature range (Travis et al., 2002). Another example, Ponater et al. (2005), found that in an ECHAM modelling study the equilibrium surface temperature response due to a Wm^{-2} forcing from contrails only produced around 60% of the response due to a Wm^{-2} forcing from CO_2. The ratio of a mechanisms response to the CO_2 response is called efficacy and, in fact, all aircraft forcings could have different efficacies compared to carbon dioxide. Table 2 presents a range of efficacies from an example model study that it relevant to aviation.

	CO_2	CH_4	O_3 Lower strat	O_3 Upper trop	O_3 subsonic	H_2O subsonic	contrails
Efficacy	1	1.18	1.8	0.75	1.2-1.56	0.14	0.59

Table 2. Efficacies for aviation and idealized ozone changes from the ECHAM model. Taken from Grewe et al. (2007) – Table 7.

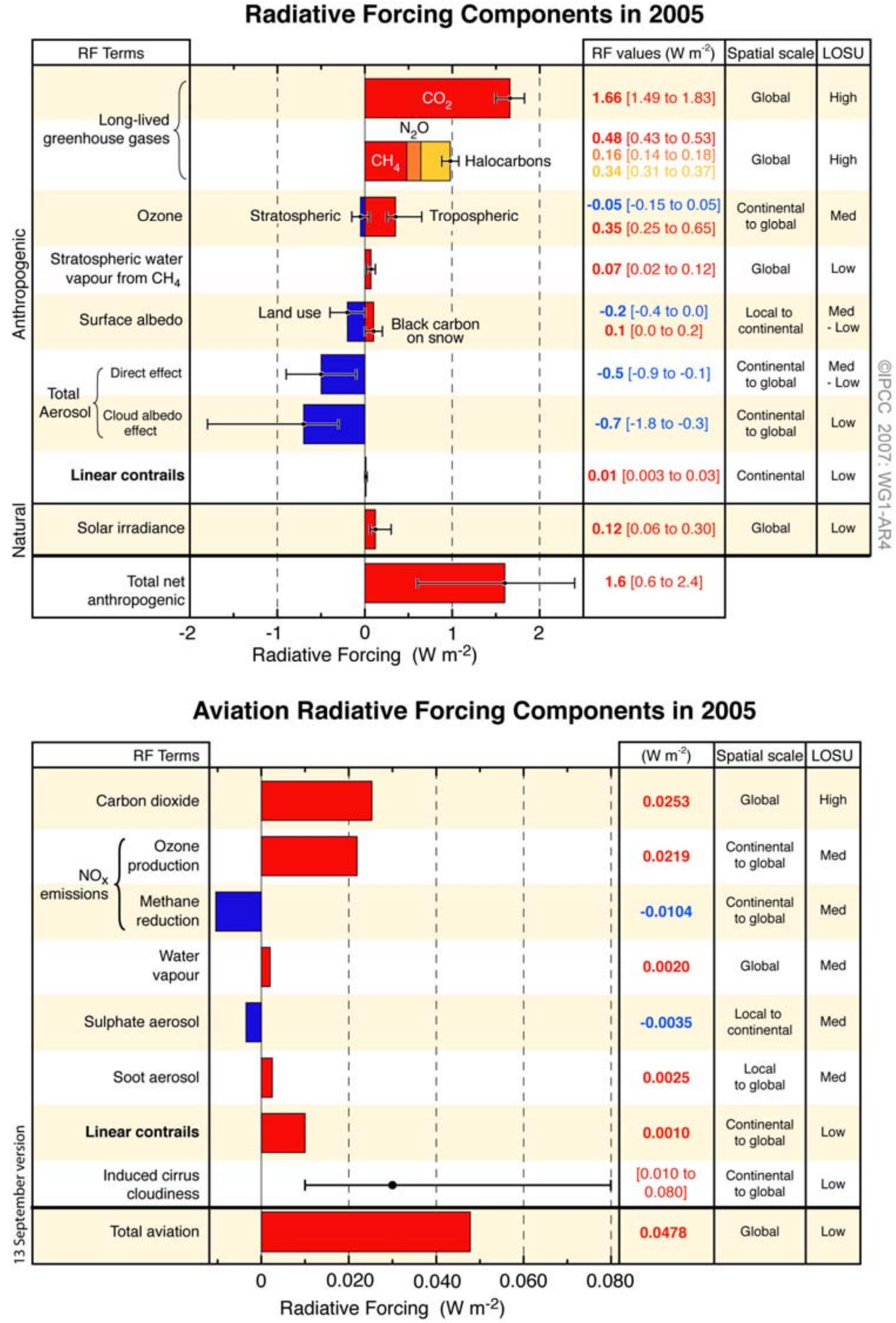

Figure 3: a) Radiative forcings from Forster et al. (2007). Showing aggregated forcing terms (implicitly including aviation effects) and b) RFs from aviation emissions, based on Sausen et al. (2005). Note that linear contrails are equivalent on the two plots. Columns represent spatial scale and level of scientific understanding. (Dave Fahey, Pers. Comm.)

The differences between the climate impact of the various aviation emissions and the trends in aviation itself need to be bourn in mind for the metric discussion which follows.

2.1.3. Review of the RF characteristics and uncertainties of mechanisms

2.1.3.1.Chemistry of importance to aviation

Aviation impacts on the atmosphere by perturbing the composition and microphysics of the system. A summary of the effects together with notes on the uncertainty of our understanding and/or modelling ability is provided in Table 3.

Effect	**Emission quantification**	**Notes**	**Effect calculation**	**Notes**
CO_2	Yes	Relatively easy – scales with fuel; **low** uncertainty	Concentration, RF	Requires historical emissions data; **moderate** uncertainty. Can validate by sales of aviation fuel
O_3	No	Secondary species formed from NO_x emissions	Concentration, RF	Secondary species formed from NO_x emissions: model-dependent, **large** uncertainty
CH_4	No	Secondary species affected by NO_x emissions:	Concentration (reduction), RF	Secondary species affected by NO_x emissions: model-dependent, **large** uncertainty
H_2O	Yes	Relatively easy – scales with fuel; **low** uncertainty	Concentration, RF	Water vapour concentrations not well characterized in UTLS; **moderate** uncertainty
Sulphate	Yes	Relatively easy if S content of fuel is known; consequently **moderate** uncertainty	Concentration, RF	S content of fuel not well characterized. Calculation of RF model dependent, requires assumptions on size distribution; **moderate** uncertainty for direct effect, **large** uncertainty for impact on cloud properties
Soot	Yes	Engine/combustor dependent, poorly characterized from measurements; **large** uncertainty	Concentration, RF	Concentrations and size poorly characterized; **large** uncertainty for both direct effect and impact on cloud properties
Contrails	No	Occurrence of contrails relatively easy to calculate if suitable atmospheric and engine data available	Coverage, RF	Coverage is model-dependent, RF model requires assumptions (size/shape of ice crystals);

				large uncertainty
Contrail-induced Cirrus	No	No current methodology for measurement/ modelling	Enhancement or coverage, RF	Coverage model/data dependent, poorly characterized optical properties; **very large** uncertainty

Table 3: Summary of aviation climate effects and their quantification (adapted from Faber et al. 2006)

The main impacts of aviation on ozone, methane and contrails/cirrus are briefly discussed below. Full details can be found in SSWPs 2,4,5 and 6.

Ozone is produced in the troposphere and lower stratosphere by photochemical oxidation of CO and HCs, catalysed by NO_x and HO_x radicals. The production rate of O_3 is mainly dependent upon the abundance of NO and HO_2, with increases in the ozone production rate with NO at low NO concentrations (Brasseur *et al.*, 1998). For NO_x concentrations between 0.1 and 0.4 nmol/mol the production rate is however predicted to reach a maximum. Above this concentration, high levels of NO_x cause a reduction of OH and hence a reduction in the ozone production rate (see figure 2-1, IPCC, 1999). As a result the change in ozone production rate due to the inclusion of aircraft emissions is highly dependent upon the background atmospheric conditions.

Methane (CH_4) is emitted from both anthropogenic and natural sources, and is a greenhouse gas. Stevenson et al. (1997) and Isaksen et al. (2001) have shown that NO_x emissions from aviation are very efficient within the upper troposphere in producing O_3 and thereby a positive impact on radiative forcing. As a result of the enhancement in NO_x and O_3 due to aviation the hydroxyl radical (OH) concentration also increases. It is this hydroxyl radical that is primarily responsible for the oxidizing capacity of the troposphere. The increase in OH significantly reduces the lifetime of CH_4 in the atmosphere and as such results in a negative radiative forcing signal due to CH_4.

Line-shaped clouds due to aviation (contrails) are formed when a mixture of hot and humid exhaust gases becomes mixed with cold ambient air in an environment saturated with respect to liquid water. This mechanism can be represented by the Schmidt-Appleman criterion (Schmidt, 1941; Appleman, 1953; Schumann, 2002) which predicts, to better than 1K, the threshold temperature for contrail formation based on the ambient pressure and relative humidity, the combustion temperature and overall propulsion efficiency, and the emission index of the water vapour from aviation. As well as the radiative importance of contrails, Borrmann et al. (1996) & (1997), Solomon et al. (1997) and Lelieveld et al. (1999) have suggested a potential role for cirrus particles in the heterogeneous chemistry of the atmosphere although further research on this topic is still required.

Radiative Effects: Emissions of NO_x result in an enhancement of O_3 concentrations with an almost global reduction in CH_4 concentrations. The enhancement of O_3 results in a positive globally averaged radiative forcing, whilst the reduced CH_4 concentrations result in a reduction in radiative forcing. As with thin cirrus clouds, contrails act to reduce the amount of both incoming short wave radiation (which acts to cool the climate system) and long-wave radiation (which acts to warm the climate system). The consensus (e.g. IPCC, 1999; Minnis et al., 2004) is that the impact on the longwave dominates such that contrails act to warm the climate.

2.1.3.2.Modelling the impact of aviation

Global chemistry transport models (CTMs) and chemistry general circulation models (CGCMs) have become paramount to our understanding of aviation's impact on the atmosphere and the possible implications for our future climate. These models are frequently used for estimating the contributions due to individual pollutant sources on regional and global scales. Of particular importance for the climate system are changes to greenhouse gases occurring in the upper troposphere/lower stratosphere (Ramaswamy et al., 2001). Ozone chemistry in the upper troposphere and lower stratosphere is particularly sensitive to NO_x and is therefore dependent upon the transport of NO_x to and from this region. The ability of a model to correctly predict the atmospheric lifetime of ozone is necessary if the impact on the hydroxyl radical, and in turn methane, is to be determined. Accurately representing these processes relies on the skill of the atmospheric model involved and as such experiments are necessary, with a variety of atmospheric models, to provide confidence in the impact of aviation on the atmosphere under varying meteorological and chemical conditions.

It is important to note that modelling the various chemical and dynamical processes occurring within this region is a particularly challenging task. For example, the correct representation of lightning activity, which in the upper troposphere/lower stratosphere (UTLS) is an important source of NO_x, is poorly quantified (Hauglustaine et al., 2001). Another important consideration for the photochemistry of the upper troposphere, is the transport, both large scale vertical ascent and rapid convective activity, of pollutants from the surface into the UTLS (Berntsen and Isaksen, 1999; Jaeglé et al., 2001). Finally, the downward transport of stratospheric ozone into the troposphere is particularly sensitive the model's dynamical formulation and together with the other mechanisms discussed briefly above can result in a large uncertainty in the ozone budget of the UTLS and therefore any perturbation to it resulting from the aviation emissions.

Models involved in the prediction of aviation's impact on the atmosphere have often shown significantly differing results both in terms of their background concentrations of key species such as NO_x and in their calculation of the perturbation to atmospheric composition due to aircraft emissions. Brunner et al. (2003) & (2005) provided a rigorous evaluation of several European CTMs and CGCMs. Comparisons were made with trace gas observations from a number of research aircraft measurement campaigns during the period 1995-1998 inclusively. Their results revealed individual model deficits and suggested areas for further improvement. In general the models exhibited a weakness in their ability to represent both trace gas mean concentrations and vertical gradients (for example, O_3, CO and NO_x) in the tropopause region. Enhanced mixing across the tropopause accounted for large-scale differences between modelled and observed CO and O_3 concentrations, with deficiencies in the biomass burning emissions having a significant impact on CO concentrations. Poor correlations between modelled and observed NO_x concentrations suggested weakness in current parameterisations of convection and lightning. In contrast, however, modelled OH concentrations showed good agreement with observations. Overall, Brunner et al. (2003) & (2005) highlighted that a better description of NO_x and NO_y chemistry, sources and sinks was probably the key to any future model improvements with regard to accurately representing the chemistry of the UTLS region and potential anthropogenic impacts.

Following the IPCC (1999) report, Rogers et al. (2002b) provided a model intercomparison of the transport of aircraft-like emissions from both sub- and supersonic aircraft. Whilst the IPCC (1999) report highlighted the variability between model calculations, the results of Rogers et al. (2002b) emphasised the importance of correctly modelling the transport processes within the lower atmosphere when determining the impact of aviation on atmospheric composition and climate. The tracer transport experiments of Rogers et al. (2002b) revealed that the transport of aircraft-like tracers across dynamical 'barriers' was particularly important. For example, in the case of supersonic aircraft-like tracers, the correct reproduction of the 'tropical pipe' was critical in isolating any sub-tropical aircraft emissions from the mid and high latitudes. By isolating emissions within the tropics, these emissions can be effectively transported up into the middle stratosphere where effective NO_x chemistry can act to reduce O_3 at altitudes of ~30-35km. Of particular importance for subsonic aircraft, the degree of stratosphere-troposphere exchange of the prescribed aircraft-like tracers revealed further differences in the transport diagnosed between the various models compared in the study. The results suggest that the variability in stratosphere-troposphere exchange may be a possible cause of the discrepancies between IPCC (1999) model values of upper tropospheric ozone resulting from subsonic aircraft emissions. Rogers et al. (2002b) state that if aircraft emissions are considered to be inactive then within the course of only two years model calculations predict that emissions from the mid-latitude upper troposphere can be transported into the polar middle stratosphere. This result highlights the importance of atmospheric models to correctly predict transport processes throughout the lower atmosphere when determining the impact of both sub- and supersonic aircraft.

Prather (2002) suggested that to quantify the full impact of a trace gas emission on the climate system it is necessary to integrate the radiative forcing effects over the lifetime of the impact. For the troposphere, Prather (1994) showed that the adjustment time of methane (estimated at 12 years by IPCC, 2001) was the critical step in determining the longest lifetime. Whilst Prather (2002) demonstrated that the cumulative impacts of an emission can be evaluated by taking the steady-state response and scaling by the steady-state lifetime of the source gas, Stevenson et al. (2004) never-the-less adopted the approach of introducing a pulse emission from aviation within a climate-chemistry model and examining the resultant change in atmospheric composition after a sufficiently long time period (100 years). Stevenson et al. (2004) showed that the size of the initial positive ozone anomaly, resulting from a pulse emission of NO_x, determines the sign and magnitude of the overall net forcing. Further work however is clearly required (for example a range of pulse sizes needs to be considered) in order to test the robustness of this result. Additional research is also required to examine the impact of a pulse emission of NO_x emitted under different atmospheric conditions and seasons (Stevenson et al., 2004 only considered emissions during the months of January and July). This is particularly important as both ozone and the hydroxyl radical exhibit strong meteorological and seasonal dependencies.

Sausen et al. (2005) summarised some of the main conclusions of the EC funded TRADEOFF project, thereby providing an update to the aviation-induced radiative forcings for the year 2000. The largest difference with those presented in IPCC (1999) resulted from the reduction, by a factor of ~3-4, of the RF resulting from (linear) contrails. The impacts due to CO_2, O_3 and CH_4 were also reduced but to a far lesser extent. Overall the total radiative forcing impact due to aviation in 2000 (not including aviation induced cirrus) was calculated at 48 mWm^{-2}, similar to the total calculated in IPCC (1999) for 1992. It is important however to note that the radiative forcing due to aviation induced cirrus is not included in either the Sausen et al. (2005) or IPCC (1999) final estimates of the total impact of aviation due to uncertainties in the magnitude of such an impact. Hartmann et al. (1992) have shown that optically thin cirrus clouds on average warm the climate system however there are examples where the radiative forcing from aviation induced cirrus can be negative (Meerkotter et al., 1999; Myhre and Stordal, 2001). Sausen et al. (2005) suggest that the total aviation RF could be significantly larger than that given in the IPCC (1999) estimate, but that further research is required not only to correctly quantify the full effect but to examine potential operational and technical procedures which could be adopted by the aviation community if the impact were to be considered as significant.

2.1.4. Regional and timescale issues

Different forcing agents have different spatial patterns (see Figure 2 and Figure 6.7 of Ramaswamy et al. 2001). These are broadly associated with timescale – the shorter a timescale of a forcing agent the more localised the pattern of radiative forcing. CO_2 and CH_4 are long-lived and have global forcing patterns, whilst contrail and O_3 forcings are shorter lived and remain fairly localized to the Northern Hemisphere and flight corridors.

Each emission can affect atmospheric concentrations and the resulting RF on different timescales. These timescales are crucial in determining the climate impact of a given emission. As outlined in Section 2.1.3, aircraft emissions are associated with multiple lifetimes. Carbon dioxide lifetime ranges from years to millennia (a tiny fraction remaining permanently in the atmosphere). As CO_2 is long-lived (having an average lifetime longer than the atmospheric circulation), a tonne of CO_2 from aviation emitted into the upper troposphere is no different than that emitted by any other surface-based industry and its concentration, and hence RF, can easily be estimated using simplified but established methods based on carbon-cycle modelling. In contrast, timescales associated with aviation NO_x emissions are different than those associated with NO_x emissions at the surface. Stevenson et al. (2004) presents a useful discussion of the various timescales. Initially NO_x produces ozone on short timescales (weeks-months), but it also decreases

CH_4, which has an associated timescale of roughly 12 years. As CH_4 in turn also affects ozone, there is also a component of ozone change that occurs on this longer timescale. Contrails, in contrast, only last for a few hours.

It is important to consider than forcings which may last no more than a few hours still influence climate for many years after, due to the time-lag of the Earth system (for example, the Earth's ocean takes decades to respond). Therefore forcings such as contrails still have a significant climate role.

Global average forcing has been a useful measure of global average equilibrium temperature response – climate models show a robust temperature response, especially when efficacy is accounted for (Forster et al., 2007). However, less work has been done on assessing how forcing relates to regional impacts. The surface temperature response certainly covers a wider area than the radiative forcing. Minnis et al. (2004) suggested a local response to aviation effects warming over the US, but this has been disputed by several studies that point to systematic flaws in the Minnis analysis. (Shine et al., 2005a, Ponater et al., 2005; Hansen et al., 2005). These modelling studies all support the view that the response to local forcing spreads over much of the globe. For example, high latitudes, generally warm more than low latitudes, even when the forcing is confined to low-latitudes (Forster et al., 2000).

Importantly, global cancellations between the responses of different forcings do not necessarily represent regional cancellation between their responses. In the metric context this is particularly important for NO_x, where the O_3 warming effect remains confined to the hemisphere of emissions and the CH_4 cooling effect occurs globally. The net effect, given the regional pattern of airline flights, is therefore a Northern Hemisphere warming and Southern Hemisphere cooling (see Figure 4).

The impact of short-lived species on the climate system is also very sensitive to the geographical location of emissions due to the inhomogenity of their distribution. In the case of NO_x emissions from aviation the resultant impact on O_3 is further complicated by the non-linearities in O_3 chemical production rates, due to its dependency upon the background composition and meteorological conditions, as well as its variable climate response depending upon latitude and altitude (Ramaswamy et al., 2001). Indeed the inhomogeneous climate response due to O_3 (resulting from emissions of NO_x) could significantly differ from that due to an identical global-mean radiative forcing response due to changes in CO_2.

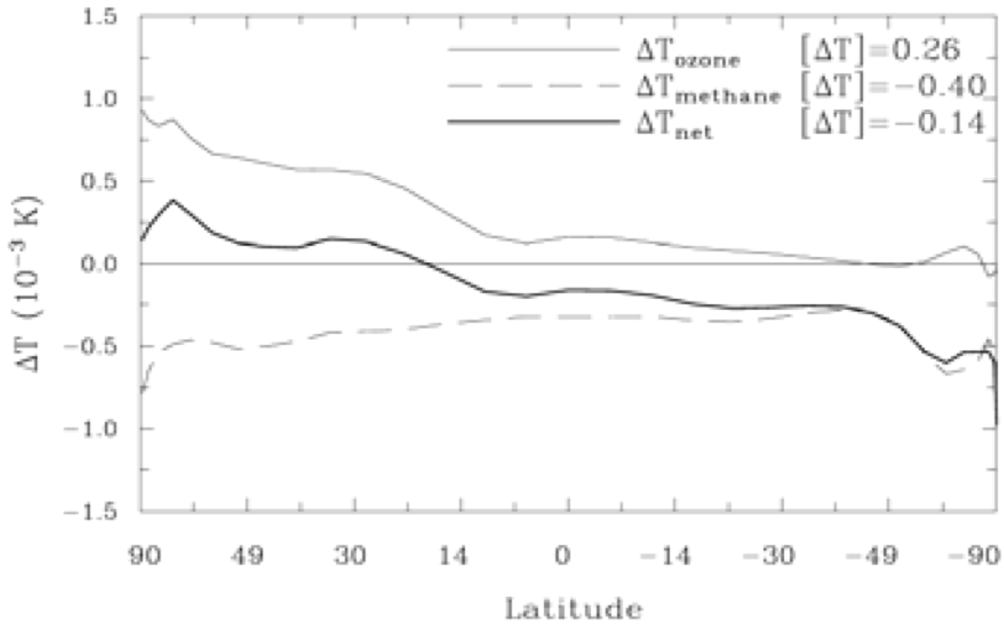

Figure 4: Surface temperature changes from calculations where an idealised emission of NO_x from the surface in Europe is traced through its impacts on ozone, methane, radiative forcing and temperature change. The surface temperature changes are shown for ozone changes only (thin solid line), methane changes only (dashed line) and the net effect (thick solid line). It shows that the strong global-mean cancellation between the two impacts (see [ ] values in legend) are made up of a northern hemisphere warming, where the ozone impact dominates over methane, and a southern hemisphere cooling where methane dominates over ozone. (From Shine et al, 2005b)

Regional climate change prediction has improved since the IPCC TAR report. However, it is still far less certain than prediction of global climate change (IPCC, 2007, Chapter 11). Regional surface temperature changes are still not adequately evaluated for aviation.

Observational studies have suggested that aviation plays a role in local diurnal temperature range change (Travis et al., 2002; 2004) and the possibility of an aviation induced weekend effect in diurnal temperature range has been mooted (Forster and Solomon, 2003). Other effects, such as surface energy budget changes, hydrological cycle effects and other climate impacts have not currently been evaluated for aviation. For future climate impact analysis these impacts are often simply associated with global mean temperature response irrespective of the cause of the temperature change itself (see Section 1).

2.2. Critical role of the specific theme

2.2.1. Advancements since the IPCC 1999 report

Section 2 and other SSWPs discuss the development of RF understanding for aviation emissions. Here we focus on metric development only. As stated in the introduction, IPCC (1999) was somewhat dismissive of aviation GWPs as a metric. Their strong statements have certainly affected the landscape of metric design not only for aviation but also for other sectors. With climate change very much on the agenda of international policy and with a need to quantify the climate impact of human emissions, metric evaluation and metric design literature has flourished. Metric design is no longer solely undertaken by physical scientists, but social scientists, economists and industry are developing a plethora of metrics to suit individual needs.

2.2.2. What is a metric?

A metric, within this context, is simply a way of comparing differing influences on climate change in a quantifiable way so that users (typically policy makers) can make informed choices about the likely climate impacts of different future scenarios. They can explicitly be used as mitigation instruments, allowing tradeoffs to be made between various policy options. The design of a suitable metric is dependent upon an explicit set of choices made by the user. These may include a knowledge of the desired *end-effect* for comparison (e.g. economic cost of climate impact, surface temperature change, sea-level rise); the timeframe over which the *end-effect* is to considered; whether the emissions are

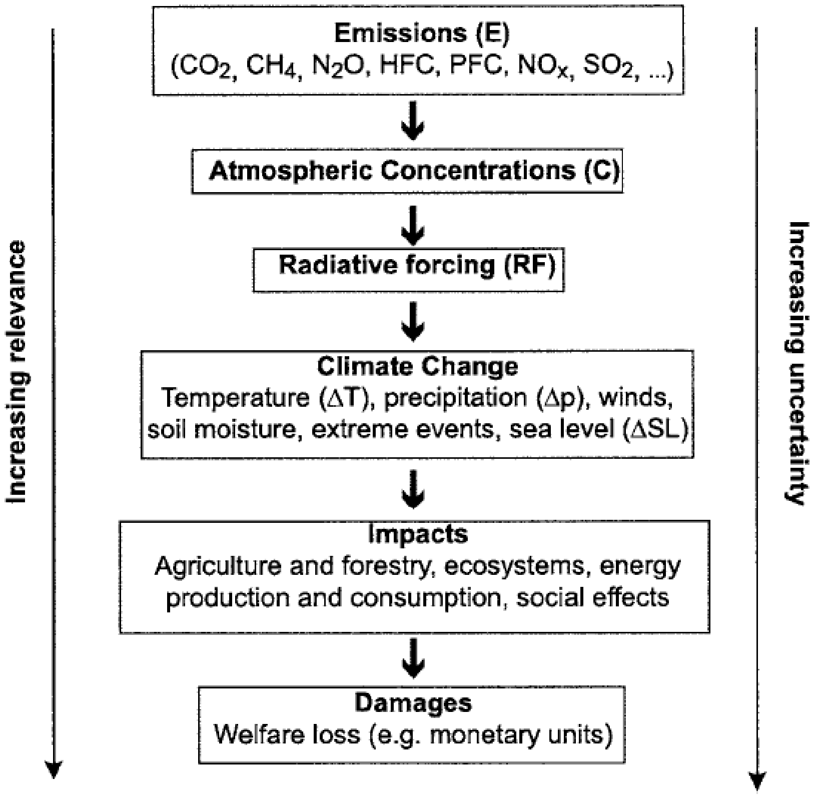

Figure 5: Cause and effect chain of the potential climate effect of emissions (from Fuglestvedt et al., 2003)

sustained or act as a pulse; and whether the metric provides an accumulation of the effects throughout the timeframe. Figure 5 shows the cause and effect chain for climate emissions. The further down the chain you can evaluate a metric, the more directly relevant a policy choice can be made for its direct impact on climate and human welfare. However, uncertainty also increases, making metrics less quantifiable and transparent.

The assumption here is that a relatively transparent and simple methodology is required for quantifying the climate impact of non-CO_2 aviation effects. Several such measures exist and have been applied to aviation specifically or more generally. Each metric has disadvantages and advantages, and within each, several parameter choices have to be made. First we discuss non-emission based metrics and then we discuss emission based metrics.

2.2.2.1.Non-emission based metrics

Non-emission based metrics with do not specifically involve emissions but have been used to quantify and understand climate change effects.

Radiative forcing: Radiative forcing can be used as a metric, it quantifies, at a given time H, the perturbation to the Earth's radiation balance over some given time period (e.g. from pre-industrial times to the present day). At H, the total forcing is due to the remaining concentrations of all radiatively-active species in the atmosphere as a result of all emissions during the given time period. In the case of aviation, emissions of CO_2 from decades before H contribute to the CO_2 concentration at time H. By contrast, for short-lived species, it is emissions near H that contribute – in the case of contrails, it will be the effect of emissions only in the few hours before H.

Radiative Forcing Index (RFI): IPCC (1999) introduced the RFI as one way of characterising the importance of non-CO_2 forcings from aviation. It is simply the ratio of the total forcing to the CO_2-only forcing. Regrettably, the concept has been mis-applied as a measure of the relative impact of non-CO_2 species of *emissions* at a given time (see Forster et al., 2006 and 2007 corrigendum, also Section 2.2.4).

Temperature response: Given a time-history of radiative forcing, the resulting global averaged surface temperature response at a time H can be calculated; often this is done using quite simple models of the climate system (e.g. Sausen and Schumann 2000, Lim et al. 2007). The thermal inertia of the climate system means that the temperature change at H is less dependent on the emissions at times near H, as the climate system will have had less time to respond to these emissions. The actual temperature response to any emission will then depend on the lifetime of the resulting forcing and the timescale of the response of the climate system.

The radiative forcing (and RFI) and the temperature change can be considered "backward-looking" metrics in the sense that they quantify the impact of all emissions prior to H and are thus dependent on the time history of emissions (or for future times, the choice of future emission scenarios). As noted above, it does not necessarily distinguish between emissions at times immediately prior to H and those long before H; this may be an issue if the question to be answered is "how much climate effect will mitigating today's emissions have?" And related to this, these metrics do not distinguish between the timescales of the different emissions, which could give a misleading impression of the impact of emission controls. As an example, the forcing due to contrails may appear to be as important as the forcing due to CO_2 (see Figure 3); however, if all aviation emissions were suddenly to cease, the contrail forcing would disappear within hours, while the CO_2 forcing would remain, albeit with decreasing importance, for many decades. In both cases, though, the temperature response remains for some time after the cessation of the forcing. Thus it is very important to define what is meant by "climate effect".

2.2.2.2. Emission based metrics

An alternative framework to the metrics above is to consider *emission* metrics, which attempt to quantify some measure of the climate impact on, for example, a per kg, or per kilometre flown, basis. Various possibilities are presented here, which are shown schematically on Figure 6.

A very general formulation of an emission metric can be given by (e.g. Kandlikar,1996):

$$AM_i = \int_0^\infty \left[(I(\Delta C_{(r+i)}(t)) - I(\Delta C_r(t))) \times g(t) \right] dt$$

Where $I(\Delta C_i(t))$ is a function describing the impact (damage and benefit) of change in climate (ΔC) at time t. The expression $g(t)$ is a weighting function over time (e.g., $g(t) = e^{-kt}$ as a simple discounting giving short-term impacts more weight) (Heal, 1997; Nordhaus, 1997; IPCC WGIII 4AR Section 3.6.1.2). The subscript r refers to a baseline emission path. For two emission perturbations i and j the absolute metric values AM_i and AM_j can be calculated to provide a quantitative comparison of the two emission scenarios. In the special case where the emission scenarios consist of only one component (as for the assumed pulse emissions in the definition of GWP), the ratio between AM_i and AM_j can be interpreted as a relative emission index for component i versus a reference component j (as CO_2 in the case of GWP).

There are several problematic issues related to defining a metric based on the general formulation given above (Fuglestvedt *et al.,* 2003). A major problem is to define appropriate impact functions, although there have been some initial attempts to do this for a range of possible climate impacts (Hammitt *et al.,* 1996; Tol, 2002, Figure 3). Given that impact functions can be defined, they would need regionally resolved climate change data (temperature, precipitation, winds, etc.) which would have to be based on GCM results with their inherent uncertainties (Shine *et al.*, 2005b). Other problematic issues include the definition of the weighting function *g(t)* and the baseline emission scenarios.

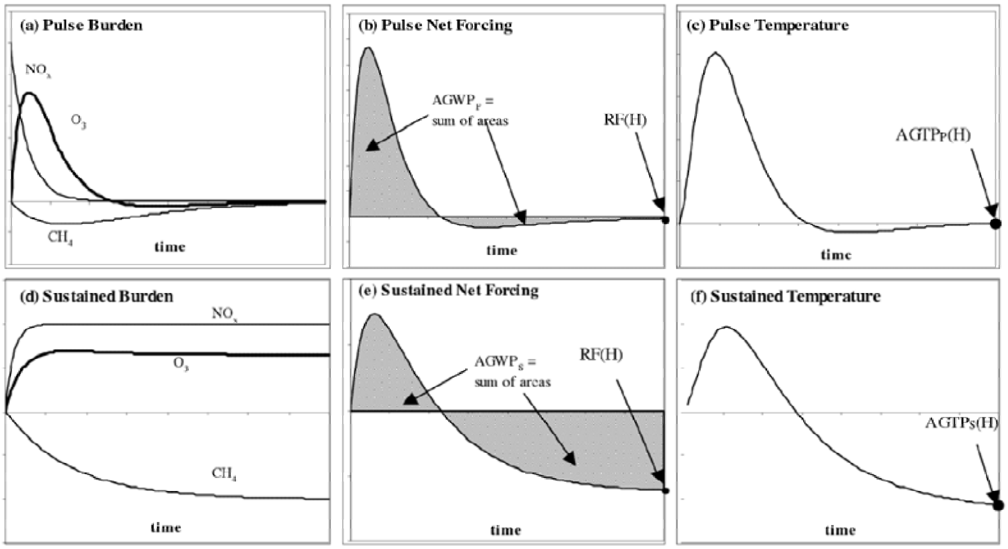

Figure 6: Schematic illustrating the possible metrics for NOx emissions that lead to perturbations both in ozone and methane. Shown are the cases of a discrete pulse emission of NO_x (top) and a sustained emission change (bottom). (a) and (d): The evolution of the concentrations of NO_x, ozone and methane. (b) and (e): The net (ozone plus methane) RF (the individual ozone and methane RFs follow the curves for the burden in (a) and (d) and the parameters that can be used for climate metrics. The absolute GWP (AGWP) is the time-integrated RF over some time horizon (H). The RF at some time H could also be used in a metric. (c) and (f): The global-mean surface-temperature change in response to the RF from (b) and (e). The absolute global temperature potential (AGTP) at some time H is another possible metric. (From Shine et al., 2005b). Note that when considering the integral of all impacts, independent of the number and atmospheric residence times of the secondary effects, Prather (2002) demonstrated that this is equal to the steady-state pattern of impacts (caused by the specified emissions) multiplied by the steady-state lifetime of the source gas for that emission pattern.

The Pulse Global Warming Potential: The standard climate metric proposed by the Intergovernmental Panel on Climate Change (e.g. IPCC 2001), and adopted by the Kyoto Protocol, is the Global Warming Potential (GWP); this is time integrated radiative forcing due to a pulse emission of a unit mass of gas. The use of the GWP is now deeply embedded and in widespread acceptance by the user community for the Kyoto group of greenhouse gases. For clarity, this will henceforth be referred to as the pulse GWP (PGWP). It can be quoted as an absolute PGWP (APGWP) (e.g. in units of $Wm^{-2}kg^{-1}$year) or as a dimensionless value by dividing the APGWP by the APGWP of a reference gas, normally CO_2. A user choice is the "time horizon" over which the integration is performed. There is no obvious choice for this; the Kyoto Protocol chooses a 100 year GWP.

For a gas x, if A_x is the radiative forcing per kg, α_x is the lifetime, and H is the time horizon then

$$APGWP^x(H) = \int_0^H A_x \exp(-t/\alpha_x)dt = A_x\alpha_x[1-\exp(-H/\alpha_x)] \quad (2.1)$$

The APGWP for CO_2 is more complicated, because its atmospheric lifetime cannot be represented by a simple exponential decay. All GWPs depends on the APGWP for CO_2. The APGWP of CO_2 again depends on the radiative efficiency for a small perturbation of CO_2 from the current level of about 378 ppm. The radiative efficiency per kilogram CO_2 has been calculated using the same expressions as in IPCC (2001), but with an updated background CO_2 mixing ratio of 378 ppm. For a small perturbation from 378 ppm the RF is 0.01413 W m^{-2} ppm^{-1}. The CO_2 response function is based on an updated version of the Bern carbon-cycle model, using a background CO_2 concentration of 378 ppm. The increased background concentrations of CO_2 means that the airborne fraction of emitted CO_2 is enhanced, contributing to an increase in the APGWP for CO_2. The APGWP values for CO_2 for 20, 100, and 500 years time horizons are 2.47×10^{-14}, 8.69×10^{-14}, and 28.6×10^{-14} W m^{-2} yr $(kg(CO_2))^{-1}$.

The Sustained Global Warming Potential: A related metric is the version of the GWP for a sustained (rather than pulse) emission (or SGWP) which gives the time-integrated radiative forcing for a sustained step change in emissions. The SGWP has been in use for a number of years, but its formulation is clearly spelt out in the appendices of Berntsen *et al.* (2005).

The change in concentration, ΔC, as a function of time for a unit mass emission is given by

$$\Delta C(t) = \alpha_x(1-\exp(-t/\alpha_x)) \quad (2.2)$$

and so the ASGWP is given by

$$ASGWP^x(H) = \int_0^H A_x\alpha_x(1-\exp(-t/\alpha_x))dt = A_x\alpha_x[H-\alpha_x(1-\exp(-H/\alpha_x)] \quad (2.3)$$

Again, the formulation of the ASGWP for CO_2 is more complex, and is given in Appendix A of Berntsen et al. (2005), using the same carbon cycle model as used for the GWP (and hence consistent with IPCC, 2001).

The Global Temperature Change Potentials: A more recently proposed group of metrics (Shine et al., 2005a) are the pulse and sustained Global Temperature Change Potential (PGTP and SGTP) which have rather different characteristics (they are "end-point" metrics i.e. the temperature change at a particular time in the future, rather than a time integrated one). Arguably the GTPs are more relevant, as they address an actual climate impact (temperature change), rather than the more abstract integrated radiative forcing. Note that although not an integrated quantity they still rely on integrating the radiative forcing over time. A disadvantage of these is that they are not accepted for widespread use. To allow a transparent formulation of the GTPs, Shine et al. (2005a) adopted a simple climate model which allowed analytical forms of the GTPs to be derived, although this is by no means a requirement. The inclusion of this climate model means that additional parameters are required to be defined – the timescale of the climate response, τ, and the heat capacity of the climate system, C (or equivalently, C and the climate sensitivity parameter, λ – the three parameters are related since $\tau=C\lambda$).

The APGTP for gas x is given by

$$APGTP^{x}(H)=\frac{A_x}{C(\tau^{-1}-\alpha_x^{-1})}[\exp(-{H}/{\alpha_x})-\exp(-{H}/{\tau})] \quad (2.4)$$

Again, a more complex relationship is required for CO_2 and (2.4) is only applicable provided τ is not equal to α. Details are given in Shine et al. (2005a).

Shine et al. (2005a) point that although the pulse form of the GTP has some appeal, it appears that the simple climate model does not well represent the response of the climate system to a pulse emission; it will be retained here for illustrative purposes only. Also, for any case where $H >> \alpha_x$ (which is often the case for aviation emissions), the PGTP will be very small, as the climate system will have "forgotten" about the pulse emission. However, Shine et al. (2007) have proposed an alternative use of the PGTP, consistent with EU policy of restricting warming below some target amount at some future time. This application shows clearly that as the target is approached, it becomes more "valuable" to reduce short-lived emissions. At times well before the target time, it is the long-lived species that exert more influence on the temperature at the target time.

The ASGTP for gas x is given by

$$ASGTP^{x}(H)=\frac{\alpha_x A_x}{C}\left\{\tau[1-\exp(-{H}/{\tau})]-\frac{1}{(\tau^{-1}-\alpha_x^{-1})}[\exp(-{H}/{\alpha_x})-\exp(-{H}/{\tau})]\right\} \quad (2.5)$$

Shine et al. (2005a) provide details of the CO_2 and $\tau=\alpha$ cases. As detailed by Shine et al (2005a), and, for long time horizons, the PGWP and SGTP asymptote to the same result, which allows an alternative interpretation of the GWP, and makes the distinction between the choice of pulse and sustained emissions arguably less important.

It would be straightforward to develop metrics which are analogous to the PGTP and the SGTP, but which consider the forcing at time H.

2.2.3. Uncertainties of metric approaches

There is considerable controversy about the application of emission metrics to assess the effect of aviation non-CO_2 emissions. IPCC (1999) stated that the global warming potential "has flaws that make its use questionable for aviation emissions" and that "there is a basic impossibility of defining a GWP for aircraft NO_x". Wit et al. (2005) echo these sentiments, concluding that "GWPs are not a useful tool for calculating the complete suite of aircraft effects". An undesirable side effect of the negative stance is that it has led some policymakers and other groups to apply the RFI as if it is some kind of alternative to the GWP (see Forster et al., 2006).

Others have taken a more pragmatic stance than IPCC, and attempted to develop GWPs for aviation emissions, whilst recognising the caveats. The first attempt appears to be by Klug and colleagues in a series of unpublished reports as part of the EC Framework 5 Cryoplane project. More recently Svennson et al. (2004) has provided GWP values for aviation, based partly on the Klug approach. Wild et al. (2001) and Stevenson et al. (2004) have generated GWP values (although they did not label them as such) for aviation NO_x emissions. These are presented in the AR4 IPCC report. Forster et al. (2006) have also quoted GWP values for a range of aviation emissions, based on the Stevenson and Wild numbers.

It is certainly true that major caveats are required in the presentation and application of any currently proposed emissions metric. However, it needs to be clearly recognised that some difficulties are not a function of the metric design but more fundamental limitations of our understanding of atmospheric processes. One example is the impact of persistent contrails on cirrus clouds; these certainly do preclude confident evaluation of values of GWPs, but the problem is much deeper than the evaluation of metrics – *any* attempt to quantify their impact, using even the most sophisticated climate models, would face similar limitations. Other limitations are more structural, such as the problem in using global-mean values for NO_x emissions, as discussed in Section 2.1.4, when compensation between negative forcings at a global level may not apply at the hemispheric level.

One other cited difficulty with emissions metrics in the context of aviation is that some effects, particularly persistent contrail production, are not clearly related to emissions by the engine. Contrails are more a function of the background atmosphere, than they are of the emissions, with the water vapour (and particulate) emissions providing a trigger. Forster et al. (2006) propose that the contrail forcing is related to CO_2 emissions, which it is argued is valid provided that a fleet-wide approach is taken, and that the height and latitude distribution of emissions remains similar to the present day fleet. Indeed this approach of using fuel use as a proxy is embedded in calculations of global mean contrail cover (e.g. Sausen et al. 1998). It has been argued that flight km is a better way of doing this, but either approach can only be applied at some time or space aggregated basis, rather than for an individual flight.

Quantification uncertainties also need to be assessed when evaluating metrics. In particular more uncertain effects should not necessarily be given an equal weight to the role of carbon dioxide emissions in which we have a good level of confidence. These uncertainties are indicated by error-bars for NO_x and contrails in Section 2.4. Efficacy (see Section 2.1.2) can also influence this judgement.

Each metric and timescale chosen essentially gives a different viewpoint on the importance of various effects. Failing to show error bars for non-CO_2 effects may not give an accurate measure of understanding. Also different metrics address different policy concerns and apply different weightings to these. They therefore factor in policy decisions (e.g. about the relative importance of temperature change in the next 20 or 100 years). These metric choices and the effects of making them need to be carefully considered. We recommend that a range of metrics covering different time periods are given.

There are uncertainties associated with GWPs. The 95% uncertainty in the AGWP for CO_2 was estimated by Forster et al. (2007) to be ±15%, with equal contribution from the CO_2 response function and the RF calculation. The uncertainties of other long lived greenhouse gas GWPs were taken to be ±20%. The simplifications made to derive the standard GWP index include, set $g(t) = 1$ (i.e., no discounting) up until the time-horizon (TH), and then $g(t)=0$ thereafter, the choice of a 1 kg pulse emission, the definition of the impact function, $I(\Delta C)$ as the global mean RF, the assumption that the climate response is equal for all RF mechanisms, and the evaluation of the impact relative to a baseline equal to current concentrations (i.e., setting $I(\Delta C_r(t)) = 0$). The criticism of the GWP metric have focused on all of these simplifications (e.g. Smith and Wigley, 2000, O'Neill, 2000; Bradford, 2001; Godal, 2003). However, as long as there is no consensus on what is the relevant impact function ($I(\Delta C)$) and temporal weighting function to use (both involve value judgements), it is difficult to assess the implications of the simplifications objectively (O'Neill, 2000; Fuglestvedt *et al.*, 2003).

Berntsen et al. (2005) have examined the climate response due to ozone perturbations resulting from regional emissions of NO_x or CO. Using a combination of chemical transport models and general circulation models they have studied the response in O_3 and OH concentrations from emission perturbations in Europe and southeast Asia. The results for radiative forcing and climate sensitivities have been incorporated to examine the potential for improving the concept of GWPs in order to represent more fully the forcings due to short-lived species. They propose a modified GWP for a sustained-step emission change which includes variations in the climate sensitivity parameter under different climate change mechanisms. Their results indicate a higher latitudinal gradient in O_3 due to NO_x emissions than calculated with CO emissions. Although they state that they are unable to conclude whether real O_3 perturbations will in general result in a different climate sensitivity from CO_2, they are able to conclude that for O_3 high-latitude emissions of NO_x lead to climate perturbations with ~10-30% higher climate sensitivities. Their results for CO however showed little regional dependency. Berntsen et al. (2005) therefore support the idea that regionally different weighting factors for the climate sensitivity parameter are necessary for emissions of NO_x whilst for CO a single global number may suffice. They note however that calculating metrics for short-lived species by necessity requires the use of atmospheric models and that the derived metrics will be more model dependent than those calculated for long-lived species.

The adequacy of the GWP concept has been widely debated since its introduction (O'Neill, 2000; Fuglestvedt et al., 2003). By its definition, two sets of emissions that are equal in terms of their total GWP weighted emissions, will not give equivalence in terms of temporal evolution of the climate response (Smith and Wigley, 2000; Fuglestvedt *et al.*, 2000). Using a 100 year time horizon as in the Kyoto Protocol, the effect of current emissions reductions (e.g. during the first commitment period under the Kyoto Protocol) that contain a significant fraction of short-lived species (e.g. methane) will give less temperature reductions towards the end of the time horizon compared to reductions of CO_2 emissions only. GWPs can really only be expected to produce identical changes in one measure of climate change – integrated temperature change following emissions impulses – and only under a particular set of assumptions (O'Neill, 2000). The GTP metric (section 2.2.2.2) provides an alternative approach by comparing global mean temperature change at the end of a given time horizon. Compared to the GWP, the GTP gives equivalent climate response at a chosen time, whilst placing much less emphasis on near term climate fluctuations caused by emissions of short-lived species (e.g. methane). However, as long as it has not been determined, neither scientifically, economically nor politically, what is the proper time horizon for evaluating "dangerous climate change", the lack of temporal equivalence does not invalidate the GWP concept or provide a guidance to replace it. O'Neill (2003) have argued that the disadvantages of GWPs are likely to be out-weighed by the advantages. This can be done by showing that the cost difference between a multi-gas strategy and a CO_2-only strategy is likely to be much larger than the difference between a GWP-based multi-gas strategy and a cost-optimal strategy (accounting for damage and mitigations costs). Thus although it has several known short comings, the GWP remains the recommended metric to compare future climate impact of emissions of long lived climate gases. although it is possible to calculate the GWP for short-lived species, these have not been adopted by policy makers for a variety of reasons (IPCC, 2001; Berntsen et al., 2005 and Shine et al., 2005b). These include for example the robustness of model simulations used to predict the response in ozone (and methane) due to an emission of NO_x, and the ability to determine the global impact resulting from regional perturbations to short-lived species.

Shine et al. (2007) have examined the dependence of the climate sensitivity parameter, λ, on a pulse emitted Global Temperature Potential (GTP). The climate sensitivity parameter was varied from 0.4 $K(Wm^{-2})^{-1}$ to 1.2 $K(Wm^{-2})^{-1}$ (as suggested by IPCC, 2001) and the impact on the time for the climate response to reach an increase of 2°C above pre-industrial times was recorded. Their results showed a marked shift in the time for the climate response from 2067 with λ=0.4 K(Wm^{-2})$^{-1}$ to 2035 with λ=1.2 K(Wm^{-2})$^{-1}$. This result clearly emphasises that any uncertainty in the climate sensitivity parameter can have a significant impact on the appropriate metric. Any application of such a metric will therefore have to include a time dependency as our knowledge of the climate system increases and we move towards the target date.

For any purely physical metric it is important to note the difficulties when attempting to maintain climate stabilisation close to and after the target time. Irrespective of these difficulties the GTP has distinct advantages over GWP not least because it is further down the cause-and-effect chain. It maintains a level of transparency similar to the GWP metric and could provide valuable information to policymakers in determining appropriate new technological and economic options.

2.2.4. Incorrect application of metrics – Radiative Forcing Index, an example

In the context of aviation, a common metric approach is to use an uplift factor of 2-3 to account for non-CO_2 effects of aviation. For example the recent inclusion of aviation within the EU emissions trading scheme has suggested an RFI value of 2 be used to compensate for the additional impacts of emissions from aircraft at altitude (see Section 3.5). The use of an uplift factor originates from a mis-application of the radiative forcing index (RFI). It is worth spending some time discussing its specific flaws here. An RFI of 2.7, calculated from the IPCC-1999 Special Report is often used as an uplift factor to weight the impact of CO_2 emissions from aviation in order to account for the non-CO_2 effects. Such an approach is scientifically flawed for a number of reasons.

1) Most importantly RFI is an instantaneous evaluation that does not account for the lifetime of emission and thereby overestimating the role of short-lived effects. This is highlighted by Forster et al. (2006) which illustrates how, with constant emissions for the year 2000, the forcings and RFI would vary with time (see Figure 7). It is important to note that due to the long lifetime of carbon dioxide, CO_2 concentrations and the associate RF increases gradually with its emission. Aviation has grown rapidly over recent decades and as a result other non-CO_2 forcings have outgrown the RF for CO_2 alone, thereby culminating in a relatively high value for the RFI.

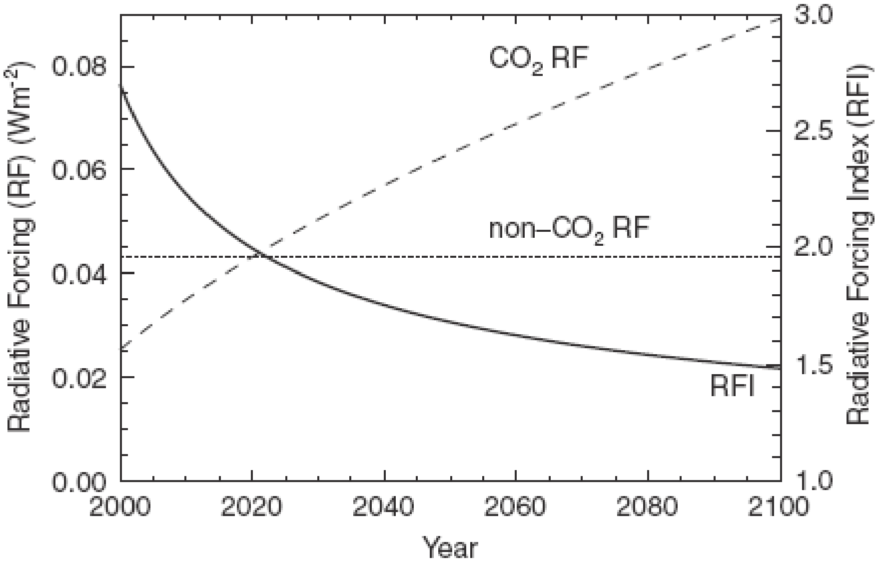

Figure 7. A scenario for sustained present-day emissions illustrating how CO_2 and its RF (dashed line) will continue to increase, whereas the non-CO2 effects (dotted line) have roughly stabilised with the emissions and are not expected to change. As a consequence of this the RFI (solid line) does not remain constant, but decreases over time (from Forster et al. 2006).

Using such a metric may not bring climate-benefit. For example the aviation industry could argue for a reduction in an uplift factor, by flying lower to produce less contrails at the expense of increased CO_2 emissions. Although in the long-term the increased CO_2 would warm climate, using an RFI metric would incorrectly predict climate benefit, where none existed.

2) The current RFI depends on past emissions, using it to evaluate future emissions is flawed. The current high value results from rapid past growth in aviation traffic, where non-CO_2 forcing effects have grown considerably faster than the CO_2 forcing. Therefore using such a metric effectively penalises the aviation industry's past rapid growth, which may be unfair. Although, if aviation continues to grow rapidly its use may be more justifiable.

3) Uncertainties are not taken into account. As discussed earlier in this section, uncertainties in the non-CO2 effects of aviation preclude an accurate evaluation of the non-CO2 forcing terms. Using latest RF estimates for aviation from Sausen et al. (2005) would reduce the RFI to around 1.9. However, if aviation induced cirrus effects were included RFI could be much bigger (~4, taking RF estimates from Sausen et al., 2005).

4) Similar uncertainties also exist for RFI as they do for the other metrics. RFI does not account for regional variation in forcing or response and it sums over very different effects, happening on different spatial scales and different timescales.

5) A similar RFI-type metric may need to be applied to other sectors for consistency (see Section 3.5). An RFI for shipping would likely be negative, due to SO_2 emissions leading to sulphate aerosol formation and an indirect effect on clouds. These effects have a larger

negative instantaneous forcing than their positive forcing resulting from CO_2 emissions. However, in the long-term ships will still produce climate warming because the long-lived CO_2 warming outlasts the sulphate cooling, yet applying such an RFI metric would suggest incorrectly that ships are actually beneficial for climate change (see Section 3.5 for further discussion).

2.3. Present state of measurements and data analysis

International assessments by WMO/UNEP, IPCC, IGAC, SPARC and EUROTRAC have all indicated that the largest uncertainties when assessing air quality and climate change result from:

- the transport of aerosols, ozone and gases that control the concentration, over long distances;
- possible changes in the oxidising capacity of the troposphere, with direct consequences for the removal of pollutants from the atmosphere;
- the potential influence of water vapour, aerosol and clouds on the climate, including trends and the indirect effect of aerosols on cloud formation;
- and variations in stratosphere-troposphere exchange as a result of climate change.

As emphasised in the WMO (2007) report, ‘changes to the temperature and circulation of the stratosphere affect climate and weather in the troposphere’, highlighting the importance of indirect perturbations to the highly-coupled atmospheric system.

The impact of aviation on the global environment occurs through the emission of gases and particles directly into the atmosphere, which contribute to global change by altering the concentration of atmospheric greenhouse gases and triggering the formation of contrails and aviation induced cirrus. Localised air pollution, in the vicinity of airports, results from the emission of gases and particles from aircraft and associated ground transport and infrastructure. It is evident that not only could the aviation industry benefit from the provision of a long term monitoring network, but that it could substantially contribute through the use of commercial in-service aircraft as observational platforms of atmospheric composition.

In the early 1970s NASA’s Global Atmospheric Sampling Programme (GASP) attempted to make regular atmospheric observations using commercial aircraft. This philosophy was again adopted in the early 1990s with research projects both in Europe and Japan. Whilst the European (MOZAIC, NOXAR) approach was to provide routine observations, Japan (JAL) opted for a biweekly ‘grab’ sampling technique. By the late 1990s this later approach was also utilised in the European CARIBIC project with an instrumented freight container for use primarily on short-haul destinations.

The EC programmes Measurement of Ozone and Water Vapour on Airbus Inservice Aircraft (MOZAIC I, II and III) demonstrated the enormous scientific value of regular observations made on board commercial aircraft in the monitoring and assessment of the causes for observed changes in air quality and climate. MOZAIC ended in 2004 having collected over 10 years worth of O_3 and H_2O vapour data, and 2 years of CO and NO_y data. This approach has been shown to provide an invaluable facility with which to maintain long term observations of the upper troposphere lower stratosphere, a region of the atmosphere notoriously difficult to monitor but critical to improving our understanding of climate change. Measurements from space and the ground in this region are difficult to perform and do not achieve the necessary spatial resolution attainable with in situ observations. Not only this, but with over 40,000 vertical profiles (obtained during landing and take-off) from more than 100 airports world-wide, a large database of observations have been made in developing countries where such data would otherwise have been difficult to obtain.

The scientific and technological expertise gained through the MOZAIC process is now being used in the design of a sustainable infrastructure suitable for routine global observations onboard a fleet of commercial aircraft. IAGOS differs from MOZAIC in many of its aims, including the design of instrument packages specifically aimed at measuring aerosol and cloud parameters, which, as stated by the IPCC, are the most uncertain contributors to climate change. IAGOS will also measure the important trace gases thereby providing information crucial to our understanding of climate change (including aviation's contribution) and the intercontinental transport of air pollution.

2.4. Present state of modeling capability/best approaches

Minimising the impact of aviation on the environment depends crucially upon the robust understanding of our atmosphere and aviation's contribution to its change. Potential areas of research cut across the disciplines of atmospheric science, economics and engineering and require a holistic view of the potential gains to be made from improved technologies (including alternative fuels) and operations. Mitigation options need to be carefully considered in order to provide accountability within all transportation sectors without inadvertently encouraging the misuse of resources which may result in environmental damage. Ongoing scientific research aims to improve our understanding of the atmosphere and the role of natural and anthropogenic emissions. A description of the major activities currently focussed on aviation's contribution to atmospheric change are described below.

In the USA, the PARTNER Center of Excellence is closely aligned with national and international needs by providing a world-class research organization with leverage from a broad range of stakeholder capabilities PARTNER fosters technological, operational, policy and workforce advances for the benefit of mobility, economy, national security and the environment, with involvement from 10 research institutes and more than 100 students. Particular emphasis is given to providing quantitative predictions and qualitative assessments of aviation noise, emissions and their impacts. A key objective of PARTNER is the improved communication and decision-making in addressing the interdependent environmental effects of aviation.

To assist in the development and communication of future strategies for a sustainable UK aviation industry, HEFCE provided financial support for a UK activity which combines academic capability with knowledge transfer to the stakeholder community. Opportunities for Meeting the Environmental Challenge of Growth in Aviation (OMEGA) is a 2 year programme of activities which started in January 2007, and aims to develop a consolidated knowledge basis within the UK; an overview of where the ‘gaps’ in our understanding remain, together with potential solutions; and a 'neutral space' for dialogue between academia and the stakeholder community.

The EC funded Integrated Project QUANTIFY aims to determine the climate impact of both present and future transport systems, including aviation, shipping and land-surface. The project, which began in March 2005 with funding for 5 years, uses improved emission inventories and more reliable models. The project provides forecasts and other policy-relevant advice with the assessment of several transport scenarios, and incorporates the exploitation of existing data with new field measurement, state-of-the-art numerical models and focused policy-relevant metrics for climate change. The project has already provided initial transport emission inventories, which have been incorporated into the appropriate modelling tools, and a variety of climate change metrics are under consideration. Through a European ‘specific support action’, ATTICA, also aims to provide a coherent set of assessments of the impact of transport emissions on ozone depletion and climate change.

2.5 Current estimates of climate impacts and uncertainties

In this section we present specific case studies in order to perform a quantitative comparison with which to evaluate different metrics on different timescales. For reasons previously discussed we only consider emission metrics here. We use 2002 emission data from AERO2K (see section 2.1.1) and associate each forcing agent with a particular emission (see Table 4). Table 4 also provides information on how each forcing agent is evaluated within these example metric frameworks.

Mechanism	Time-scale (alpha)	Associated emission source	Notes
Carbon dioxide	Multiple	CO_2	Metric evaluated with 4 term approximation to Bern carbon cycle model (Shine et al. 2005a)
Short-lived ozone production from NO_x	Weeks-month	NO_x	100 yr GWPs taken from Stevenson et al. (2004) or corrected Wild et al. (2001). For other time horizons assumes alpha(CH_4) is 11.53 years alpha(O_3) is 0.1 year
Methane reduction from NO_x	~12 Years	NO_x	
Ozone reduction from methane loss	~12 Years	NO_x	
Contrails	Hours	Distance travelled by aircraft fleet, assumed to relate to CO_2 emissions	No associated emission, but assumed to be CO_2 for simplicity. Using AERO2K and IPCC (2007) numbers the associated metrics are calculated assuming that 550 Tg CO_2 corresponds to an RF of 10 mW/m^2, with a factor of three uncertainty

Water vapour	Days (troposphere); few years (stratosphere)	Water vapour	Not evaluated here as only thought significant for supersonic fleet
Aerosols	Days-week	SO_2, soot	Not evaluated – believed to be small effect
Aviation induced cirrus	Hours-days	N/A	Very uncertain for evaluate of metrics. However, as an example, A range of AIC values is used based on an RF between 10 mWm^{-2} and 80 mWm^{-2} with a best estimate of 30 mWm^{-2}. These rough values are taken from Forster et al. (2007), Table 2.9. These RFs are assumed to correspond to 550 Tg CO_2

Table 4: Mechanism characteristics for metrics

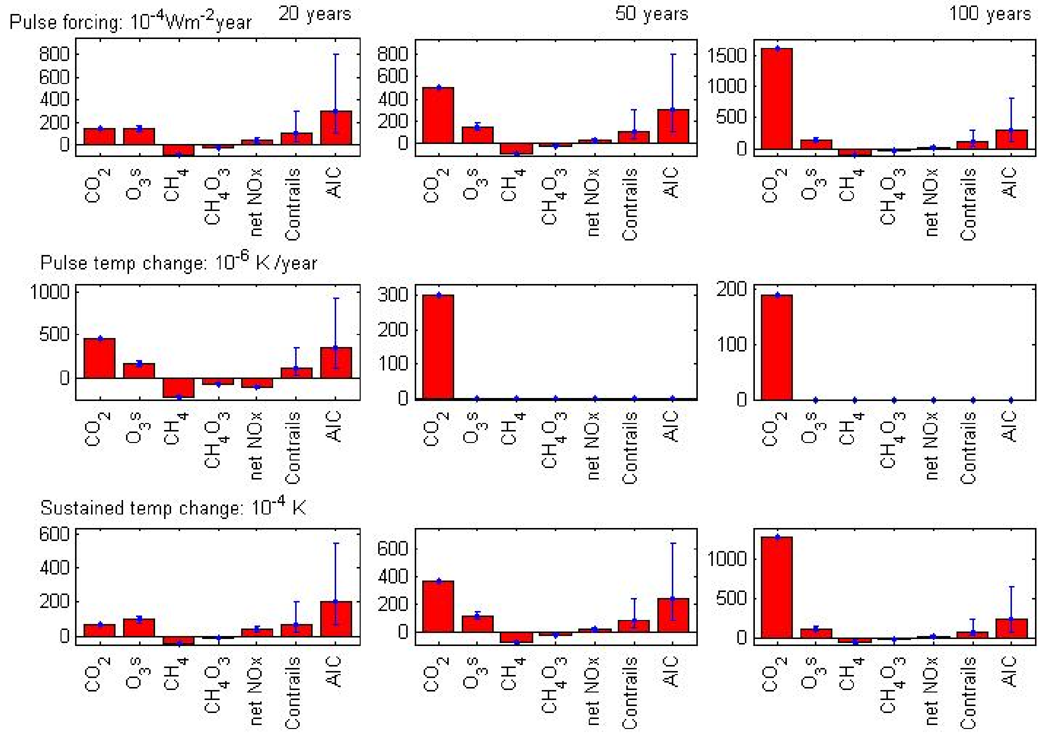

Figure 8: Examples of the use of three metrics using AERO2K emissions (rows: using PGWP, PGTP, SGTP to evaluate climate effect) evaluated at three time horizons (columns: 20, 50, 100 years). Units are 10^{-4} Wm^{-2}year (row 1); 10^{-6} K $year^{-1}$ (row 2); 10^{-4} K (row 3). NO_x evaluations are based on averages of Stevenson et al. 2004 and Wild et al. 2001 numbers. AIC is aviation induced cirrus. Note that the scale on the y-axes varies between frames. Note that no uncertainty is given for CO_2 as there are none which are specific to their evaluation in the context of aviation. Typically quoted uncertainties for CO_2 are ±10%.

As examples of variation between metric choices, three metrics are evaluated in Table 5 (pulse GWPs, pulse GTPs, and sustained GTPs), for three time horizons (20 years, 50 years and 100 years).Table 5 presents the “per kg emitted” metrics. To evaluate the actual impact of a fleet, these values must be multiplied by the actual mass emissions. Figures 8 and 9 do this for the AERO2K fleet (Table 1).

Uncertainties also need to be assessed when evaluating metrics. In particular more uncertain effects should not necessarily be given an equal weight to the role of carbon dioxide emissions in which we have a good level of confidence. These uncertainties are indicated by error-bars for NO_x and contrails. Efficacy (see Section 2.1) can also influence this judgement. Ponater et al. (2005) suggest that the efficacy for contrails is roughly 0.6, which would mean that the contrail numbers in Table 5f could be weighted by this factor, reducing their overall contribution.

Figure 8 shows that at the 20-year time horizon, the short lived emissions are competitive with CO_2 for all three metrics. The net NO_x effect varies between the cases but all three metrics tell a generally similar story. At longer time horizons, CO_2 becomes increasingly dominant, especially using the PGTP. The values using PGWP and SGTP become increasingly similar at long time horizons.

Figure 9 presents an emissions form of an RFI where the total impact is divided by the CO_2 only effect. Figure 9a neglects the highly uncertain aviation induced cirrus (AIC). It illustrates that the emissions index tends to 1 (i.e. CO_2 dominance) as the time scale increases, especially when using the PGTP. However, for the 20 year time horizon, the non-CO_2 effects are clearly important when using the PGWP and SGTP, a characteristic that could become even more marked if a shorter time horizon was chosen.

Figure 9b shows the impact of including the AIC, which has a particularly marked impact at shorter time horizons. Figure 9c excludes the AIC but, for illustration, assumes that the efficacy for contrails is 0.6, following Ponater et al. (2005), this acts to reduce the effect of the short lived emissions, enhancing the dominance of CO_2.

As emphasized in Section 2.2, the choice of metric and time horizon depends on the application to which the metrics are put, and there appears some merit in presenting multiple indices/horizons, to illustrate these dependencies.

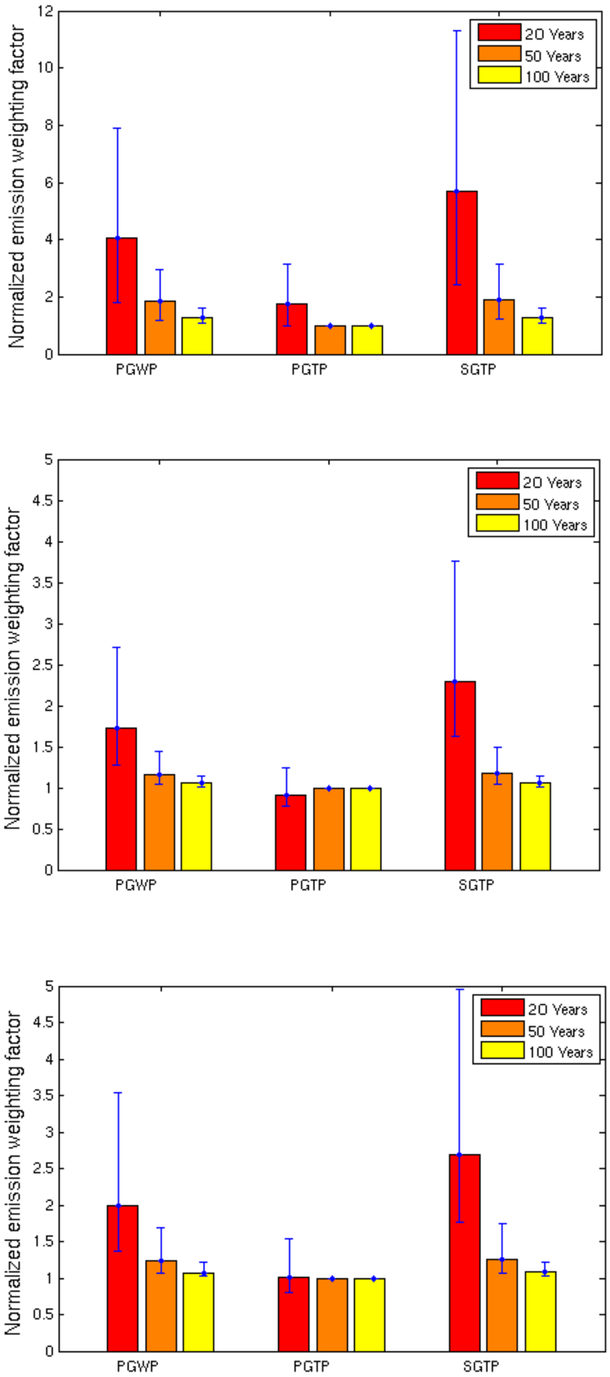

Figure 9. Summary of Figure 8, where total aviation impact has been normalized to CO_2 *impact creating an emission weighting factor appropriate to the current fleet. Error bars present uncertainties arising from NOx and contrail forcings. Top: excluding the highly uncertain aviation induced cirrus (AIC). The uncertainties are the range of values presented in Table 5. 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.*

a) Carbon dioxide (using Shine et al., 2005 parameterization)

	Time Horizon (years)		
Metric	20	100	500
APGWP (x10^{-14} Wm^{-2}kg(CO$_2$)$^{-1}$year)	2.7	9.1	29
APGTP (x10^{-16} Kkg(CO$_2$)$^{-1}$)	8.3	5.5	3.5
ASGTP (x10^{-14} K(kg(CO$_2$) year^{-1})$^{-1}$)	1.2	6.7	23

b) NO$_x$ ozone production on short timescales. Stevenson (Wild)

	Time Horizon (years)		
Metric	20	100	500
APGWP (x10^{-14} Wm^{-2}kg(NO$_2$)$^{-1}$year)	510 (790)	510 (790)	510 (790)
APGTP (x10^{-16} Kkg(NO$_2$)$^{-1}$)	590 (920)	0.33 (0.52)	0.0 (0.0)
ASGTP (x10^{-14} K(kg year(NO$_2$)$^{-1}$)$^{-1}$)	340 (530)	410 (630)	410 (630)

c) *NO$_x$ induced CH$_4$ reduction. Stevenson (Wild)*

	Time Horizon (years)		
Metric	20	100	500
APGWP (x10^{-14} Wm^{-2}kg(NO$_2$)$^{-1}$year)	-350 (-380)	-420 (-460)	-420 (-460)
APGTP (x10^{-16} Kkg(NO$_2$)$^{-1}$)	-900 (-990)	-3.4 (-3.7)	0.0 (0.0)
ASGTP (x10^{-14} K(kg year(NO$_2$)$^{-1}$)$^{-1}$)	-180 (-200)	-340 (-370)	-340 (-120)

d) *Long-term ozone loss from CH$_4$ changes. Stevenson (Wild)*

	Time Horizon (years)		
Metric	20	100	500
APGWP (x10^{-14} Wm^{-2}kg(NO$_2$)$^{-1}$year)	-78 (-130)	-95 (-150)	-95 (-150)
APGTP (x10^{-16} Kkg(NO$_2$)$^{-1}$)	-200 (-330)	-0.77 (-1.2)	0.0 (0.0)
ASGTP (x10^{-14} K(kg year(NO$_2$)$^{-1}$)$^{-1}$)	-41 (-65)	-76 (-120)	-76 (-120)

e)*Net NO$_x$ Changes associated with all methane and NOx effects. Stevenson (Wild)*

	Time Horizon (years)		
Metric	20	100	500
APGWP (x10^{-14} Wm^{-2}kg(NO$_2$)$^{-1}$year)	82 (286)	-8.8 (178)	-8.9 (178)
APGTP (x10^{-16} Kkg(NO$_2$)$^{-1}$)	-510 (-390)	-3.8 (-4.4)	0.0 (0.0)
ASGTP (x10^{-14} K(kg year(NO$_2$)$^{-1}$)$^{-1}$)	120 (270)	-6.7 (140)	-7.1 (140)

f) *Contrails, assuming 10 mWm^{-2} for 550 Tg CO$_2$, factor of three uncertainty*

	Time Horizon (years)		
Metric	20	100	500
APGWP (x10^{-14} Wm^{-2}kg(CO$_2$)$^{-1}$year)	1.8	1.8	1.8
APGTP (x10^{-16} Kkg(CO$_2$)$^{-1}$)	2.1	0.0	0.0
ASGTP (x10^{-14} K(kg(CO$_2$) year^{-1})$^{-1}$)	1.2	1.5	1.5

g) *AIC, assuming 30 mWm-2 for 550 Tg CO2, range based on an RF between 10 mWm-2 and 80 mWm-2. These ranges are taken from Forster et al. (2007), Table 2.9.*

	Time Horizon (years)		
Metric	20	100	500
APGWP (x10^{-14} Wm^{-2}kg(CO$_2$)$^{-1}$year)	5.5	5.5	5.5
APGTP (x10^{-16} Kkg(CO$_2$)$^{-1}$)	6.3	0.0	0.0
ASGTP (x10^{-14} K(kg(CO$_2$) year^{-1})$^{-1}$)	3.7	4.4	4.4

Table 5: Absolute values of the metrics for 3 different time horizons. a) for carbon dioxide emissions. b) Short lived ozone production from NO$_x$ emissions. c) CH$_4$ reduction from NO$_x$ emissions. d) The longer timescale ozone change associated with the CH$_4$ reduction. e) the net effect of NO$_x$ emissions (i.e. the sum of (b), (c) and (d)). f) contrails, based on CO$_2$ emissions. Contrails metrics are given in terms of CO$_2$ and have an associated uncertainty that is estimated to be a factor of three. g) Aviation-induced cirrus (AIC) based on CO$_2$ emissions. A range of AIC values is used based on an RF between 10 mWm^{-2} and 80 mWm^{-2}. These ranges are taken from Forster et al. (2007). Metrics in Tables b)-e) are quoted in terms of NO$_x$ emission. Uncertainties are evaluated by quoting numbers from the two available studies (Stevenson et al., 2004 and Wild et al., 2001).

2.5. Interconnectivity with other SSWP theme areas

The magnitude of any climate response due to aviation will rely heavily on our understanding of the background atmosphere (composition and meteorology) as well as our ability to accurately represent any perturbations to the atmosphere due to aviation. This SSWP will inevitably draw upon the conclusions and recommendations found in all other SSWPs. It is important however to note that other SSWPs may not be dependent upon the outcomes of this SSWP which is aimed at providing an overview of the metrics available for comparison of the climate impacts due to aviation.

3. Outstanding limitations, gaps and issues that need improvement

3.1. Science

- Assessment: It is now over 7 years since the publication of the IPCC Special Report on Aviation and the Environment and during this time substantial advances to our understanding have been made. It is therefore timely to consider whether a new IPCC report, again focusing on aviation and/or the transportation sector as a whole, should be instigated. The specific support action ATTICA started in June 2006 and will provide 3 assessment reports covering the impact of emissions from the individual transport sectors: land traffic; shipping and aviation. A further assessment will consider the metrics that describe, quantify and compare the atmospheric impacts of transport emissions. It is important to note however that focus within ATTICA will be given to European research. Godal (2003) also suggested that an assessment of the literature on alternative approaches to the use of GWPs as a suitable metric of climate change is necessary, and that this would not only represent a major step forward in improving our understanding of these issues, but that it is necessary if a different metric is to be implemented in the future. An assessment of this kind may in turn generate further studies on the political feasibility of various metrics, a critical issue when it comes to their implementation. A further discussion of these policy-related issues is given in Section 3.4.[*Priority Task As1a & b, Section 4*]

- Efficacy: Joshi et al. (2003) found that, in a study of three GCMs, the climate sensitivities (λ), defined as the ratio of the globally averaged surface temperature change to radiative forcing, revealed generic deviations from a base case with global CO_2 perturbations. In general, upper tropospheric O_3 increases produced lower values of λ whilst lower stratospheric O_3 perturbations lead to higher values of λ. Extratropical forcings also indicated higher λ values than found for tropical forcings. Forster et al. (2007) also found that the efficacies were within about 50% of 1.0 for a range of mechanisms and models. The efficacy for contrails was considerably smaller than 1.0 in one model (Ponater et al., 2005). Further examination of the efficacy for contrails and ozone especially are needed in a variety of different models to understand this further. [*Priority Task A1, Section 4*]

- Impact of local effects on regional/global change – variations with metrics: A modelling intercomparison is required to examine the impacts of local radiative effects (e.g. contrails, ozone) on global climate change. Historically the radiative responses due to all effects were added together irrespective of either their sign or geographical extent. It is this addition of the effects that has led to the formulation of a radiative forcing index (RFI) for aviation of 2.7 (IPCC, 1999) in order to account for the non-CO_2 effects of aviation. The true impact of all radiative effects (positive and negative, local and global) on the climate system therefore needs to be addressed in order to confirm whether an additive approach is appropriate. [*Priority Task A2, Section 4*]

- Timescales: Probably as a result of convenience and simplicity, the chosen metric to compare the climate impact of these greenhouse gases was the 100-year Global Warming

Potential (GWP) as calculated by the Intergovernmental Panel of Climate Change Second Assessment Report (IPCC, 1995). The 100 year timescale may have been chosen arbitrarily as this was the middle value of 20, 100 and 500 year GWPs presented in the report. A full assessment of the range of impacts, using a spectrum of metrics and timescales, should be conducted with a variety of models on a single future climate scenario. Note the decision of timescale has a large socio-political element involved and also impacts discount rates - do we care as much about our grandchildren as our children, and what about our great, great grand children? (see Section 3.4). [*Priority Task A3, Section 4*]

- Cancelling negative and positive effects: Metrics could be adopted which consider local inputs (averaged globally) rather than global mean inputs. One difficulty with this approach however is the degree to which the local impact on the climate system remains local and whether the amount of 'spread' varies depending upon the mechanism (species) responsible for the initial climate change. [*Priority Task A4, Section 4*]

- Pulse emissions, sustained emissions or realistic scenario: Using pulse or sustained emissions can give very different interpretations of climate impact (See Section 2.4). Advantageously, pulse and sustained emissions lead to simple often analytic reproducible metrics that are not prejudicing the future scenario of aviation emissions and would be more or less invariant with time. However, choosing a realistic growth scenario (e.g. Lim et al 2007; Wit et al. 2005) can give a more relevant metric. For example, if aviation continues to grow at an exponential rate, aviation's non-CO_2 effects on climate change would remain proportionally similar to CO_2 as that expected using the current radiative forcing index of around 2, whereas using a GWP metric would underestimate the role of non-CO_2 effects. [*Priority Task A5, Section 4*]

- Background scenario: The background scenario choice affects metric evaluation. Further, as background atmospheric composition and temperature changes into the future metric values will change. The most obvious and predictable change is that as concentrations of CO2 rise its radiative effect saturates, therefore non-CO2 effects become more significant. A question leads from this as to whether metrics, when is use, should be revaluated from time to time depending on the current background atmosphere. Also development of knowledge and understanding could lead to future metric re-evaluation. [*Priority Task A6, Section 4*]

3.2. Measurements, analysis and modelling capability

IPCC (2001) highlighted that 'further action is required to address remaining gaps in information and understanding'. Focus should therefore be given to the necessary research needed in order to improve the ability to detect, attribute and understand climate change, with a reduction in the uncertainties, and an aim to forecast future perturbations. Special emphasis should also be given to the need for additional long term observations following the decline in monitoring networks, an effort encouraged by the IPCC report. Together with improved observational capacity however is the need for appropriate modelling and process studies. Of relevance to the aviation industry, the IPCC report notes:

'Systematic observations and reconstructions:

- Reverse the decline of observational networks in many parts of the world
- Sustain and expand the observational foundation for climate studies by providing accurate, long term, consistent data including implementation of a strategy for integrated global observations
- Improve the observations of the spatial distribution of greenhouse gases and aerosols

Modelling and process studies:

- Improve understanding of the mechanisms and factors leading to changes in radiative forcing
- Improve methods to quantify uncertainties of climate projections and scenarios, including long-term ensemble simulations using complex models
- Improve the integrated hierarchy of global and regional climate models with a focus on the simulation of climate variability, regional climate changes and extreme events.'

As stated in IPCC (2007) one of the largest uncertainties in predicting future climate change is still related to the potential impact of aerosols and clouds on the global radiation budget. These uncertainties are critical to determining the full contribution of aviation to total anthropogenic climate change. Additional research on contrails and aviation induced cirrus (including their occurrence and radiative properties), together with the provision of data on aerosols, clouds and radiatively active gases and precursors, is paramount to the construction of appropriate mitigation options.

An initial report of findings and recommendations by the PARTNER and the USA Joint Planning and Development Office, based on a workshop on The impacts of aviation on climate change, June 2006, (recently published in summary form by Wuebbles et al. 2007) highlighted the need for focused research efforts to 'address uncertainties and gaps in our understanding of current and projected impacts of aviation on the climate and to develop metrics to characterise these impacts'. They also went further to suggest that this could be achieved through the coordination and/or expansion of existing and planned climate research programmes together with new activities. The short term research needs identified, included:

- A model and measurement intercomparison.
- In-situ probing and remote sensing (including space-borne sensors) of aging contrail-cirrus and aircraft plumes.
- Regional modelling studies of supersaturation and contrail formation, including evaluation of satellite observational capability.
- Calculation of radiative forcing from cirrus and contrails including studies of efficacy.
- Exploration of alternative metrics including their reliability.

In the long term the following were suggested:

- Field campaigns to examine HO_x-NO_x chemistry in the upper troposphere.

- Forecasting methods for supersaturation (possibly based on commercial aircraft measurements).
- Development of prognostic methods for the calculation of cloud fraction within atmospheric models.

3.3. Interconnectivity with other SSWP theme areas

See Section 2.8

3.4. Interconnectivity with comprehensive transport policy

3.4.1. Policy interface issues

Lee & Sausen, 2000 concluded that if aviation participated in an open regime of CO_2 emissions trading (i.e. intersector with capped global CO_2 emissions), where overall aviation was a purchaser of CO_2 permits from other sectors, the result would be a larger radiative forcing from aviation emissions (including NO_x) than if the emissions had originated from sectors operational at the Earth's surface. Alternatively, if aviation participated in a closed regime of CO_2 emissions trading (i.e. intrasector with capped global CO_2 emissions) the total radiative forcing from aviation emissions could be greater or lesser depending on the temporal and geographical location of emissions. It is therefore possible to envisage a scenario where the effects of emissions trading with capped global CO_2 emissions could increase the radiative forcing from aviation.

This section is provided to give a short perspective of the way metric use may depend on the policy question being asked. It is emphasized that the authors of this report are climate scientists, and are not experts in policy issues. It presents one, perhaps rather limited, perspective on this issue.

The overall stated aim of the UN Framework Convention on Climate Change (UNFCCC) (http://unfccc.it) is to stabilise greenhouse gas *concentrations* at a level that will avoid dangerous climate change; the required level has not been defined and is the subject of intense debate. The Kyoto Protocol, which incorporates the UNFCCC set emission targets, relative to 1990 levels, for signatories to the treaty. These emission targets do not appear to have stabilisation, let alone a defined stabilisation target, in mind. The targets are set in terms of CO_2 equivalent emissions for 6 groups of greenhouse gases (CO_2, N_2O, CH_4, the HFCs, the PFCs and SF_6), where CO_2 equivalence is determined using the 100 year (pulse) GWP. The Kyoto Protocol covers the period up until 2012 with the negotiations for the period beyond 2012 currently active. It is not clear whether any new protocol would include emissions beyond the group of six gases mentioned above. It could be argued that for consistency with the operation of the Kyoto Protocol, the 100-year GWPs, despite all the caveats in their derivation, are the most appropriate metric to use in assessing non-CO_2 emissions from aviation.

The 100 year timescale may have been chosen arbitrarily as this was the middle value of 20, 100 and 500 year GWPs presented in the report. It is also interesting to note that since the Second Assessment Report (IPCC, 1995) there has been considerable revision to many of the 100-year GWPs (e.g. the methane GWP has increased by over 25%), yet all accounting under the Kyoto Protocol retains values from the original IPCC (1995) report. Cost effectiveness of mitigation policy would likely improve with more accurate metrics. Yet there is also an argument for a consistent policy landscape, allowing businesses and sectors to make longer-term plans. These issues need to be considered when developing new metrics.

More recently, the European Union has adopted a more specific target stating that the global annual mean surface temperature increase should not exceed 2ºC above pre-industrial levels. (www.europa.eu/bulletin/en/200503/i1010.htm). It has been argued (see for example Shine et al. 2007 for discussion and references), that metrics like the GWP are ill-suited to such targets. The argument is that the GWP places equal emphasis on emissions of long and short-lived gases, irrespective of when they are emitted. The argument then follows that at times distant from when the target will be achieved, the emphasis should be on the longer-lived gases; emissions of short-lived gases will have only a small impact on climate change at the target time. However, as the time of the target is approached, increasing emphasis should be placed on the short-lived gases, as their influence on temperatures becomes greater. Hence, in this view, the value of metrics, relative to CO_2 changes as the target is approached. Results indicate that it is only at times less than 20 years before the target is reached that aviation's non-CO_2 emissions become important. Before that time CO_2 emissions are the dominant effect. Such arguments assume that the rate of change of climate is much less important than the total change at some distant point.

Multi-component abatement strategies to limit anthropogenic climate change need a framework and numerical values for the trade-off between emissions of different forcing agents (gases and aerosols). GWPs or other emission metrics provides the necessary tool to operationalize comprehensive and cost-effective policies (Article 3 of the UNFCCC) in a decentralised manner so that multi-gas emitters (nations, industries) can compose cost-effective mitigation measures according to a specified target by allowing for substitution between different climate agents. The metric formulation depends on whether a long-term target to comply with the UNFCCC goal of avoiding dangerous climate change is set (either by a cost-benefit analysis or by a more political judgement), or if we are concerned about reducing the impacts of climate change, but so far have not agreed on any specific long-term target (as in the Kyoto Protocol). In both cases the metric formulation requires knowledge of the contribution to climate change from emissions of various components over time, i.e. their radiative efficiency and atmospheric residence time. In addition, both formulations also involve input from economics. Economists have argued that, ideally, the metric should be the outcome of an analysis that minimizes the discounted present value of damages and mitigation costs (e.g. Manne and Richels, 2001). If a climate forcing reduction trajectory is formulated to achieve a long-term target the proper trade-off between gases is then their relative contribution to that trajectory, that is, the ratio of the shadow prices[1]. Otherwise, if a long-term target is not set, the proper trade-off is the relative contribution of various gases to the impacts, that is, the ratio of the marginal damage costs[2]. Substitution of gases within an international climate policy with a long-term target and including economic factors is discussed in Sections 3.3.2 and 3.6 of IPCC WG III AR4.

The UNFCCC has requested that the International Civil Aviation Organisations (ICAO) takes action on aviation emissions in recognition that a global approach is crucial to the success of any action. In response ICAO has formed a Committee on Aviation Environmental Protection (CAEP) with current tasks including the development of guidance for states wishing to participate in emissions trading schemes and an improved understanding of the potential tradeoffs between improvements in emissions of CO_2 and the effect on other environmental effects. It is important however to note that the current tasks within ICAO-CAEP do not themselves constitute the regulation of emissions. The international co-ordination of taxes is difficult to implement since it is contrary to the ICAO rules to levy the tax on fuel carried on international flights. The majority of bilateral air service agreements responsible for regulating international air travel also forbid air fuel taxation. It is manly for this reason that the level of taxation experienced by the aviation industry is currently low relative to road fuel taxes.

ICAO has recently endorsed the concept of emissions trading schemes for the aviation industry and the European Union (EU) has now released a Directive to include aviation within the EU's emission trading scheme with a view that the guiding principles can be replicated in a workable worldwide model. For example, the EU suggest that the coverage must be clear (e.g. including domestic, intra-European Union and all flights landing or leaving the EU), trading entities should be all aircraft operators and carriers, and the allocation of permits should occur at the EU level. Importantly they have voted for a multiplier, of at least two, to be used to compensate for the additional impacts of emissions from aircraft at altitude. The Stern Review (2007), chapter 15, suggested that the auctioning of permits would raise valuable revenue and increase the speed of adjustment to a carbon market. Not only this, but combining emissions trading with taxation could provide additional revenue with strong incentives towards innovative approaches to reduce aviation emissions. The EU emissions trading scheme states that for aviation only 25 percent of emissions permits are to be auctioned (with an option to increase this at a later date).

The Stern Review (2007) stated that the ultimate choice in taxation, trading or alternative economic instruments is likely to be driven as much by political viability as by economics. It was also suggested that a lack of international co-ordination could lead to serious carbon leakage as the aviation sector would be incentivized to fuel-up in countries where carbon pricing was not included. The Stern Review (2007) went further however

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[1] The shadow price of gas g is the reduced cost of meeting the desired policy if we were allowed to emit one extra unit of gas *i* at time *t*. This shadow price therefore tells you the cost benefit of slightly relaxing the emission constraint.

[2] The marginal damage cost is the economic cost of climate impact per unit increase in an emission (e.g. impact measured in dollars per tonne of CO2 emitted or dollars per tonne of NOx emitted)

to recommend that any carbon price faced by aviation should reflect the full climate change contribution due to emissions from aviation and noted that non-CO_2 effects should be included, through the design of an appropriate tax or trading scheme, and that a form of discounting could be used analogous to GWPs. Uncertainties in the conversion of CO_2 emissions into the full CO_2 equivalent quantity were however highlighted.

Voluntary approaches to a reduction in the climate impact of aviation are also important. Existing international co-operation through, for example, the Advisory Council for Aeronautics Research in Europe (ACARE) requires that all new aircraft produced after 2020 be 50% more fuel efficient per passenger seat kilometre relative to an equivalent aircraft in 2000. Currently these targets, though technically challenging, are broadly on track. Similar goals have also been set in the USA through the National Aeronautics and Space Administration (NASA).

3.4.2. Interface with air-quality

Global averaged GWPs can be calculated for short-lived species (e.g. ozone precursors and aerosols). On a global level the mean metric values can be used to give an indication of the total potential of mitigating climate change by including a certain forcing agent in climate policy. As discussed by Hansen and Sato (2004) and Rypdal et al. (2005) there might be a potential for more effective climate mitigation strategies if climate mitigation and air quality issues are viewed together. Assessing the climate impact of key species affecting air quality is therefore needed. However, the metric values for short-lived compounds vary significantly by region and time so that for operationalization on a decentralized level, robust regionally varying GWPs must be established and agreed upon. Improved scientific understanding of O_3 chemistry and the climate effects of aerosols are needed before this can be established, with the possible exception of carbon monoxide (Berntsen et al., 2005). A more fundamental question related to the application of GWPs for short lived species is whether the more short-term climate fluctuations caused by pulse emissions of these components should be weighted equally to long-term climate warming by long lived gases, as is implicitly assumed through application of the GWP concept. However, as long as there is no consensus on what constitutes ‘dangerous anthropogenic interference with the climate system’ there is no clear conclusion to this question. A more long term perspective, e.g. by calculating the contribution from current emissions to climate change at a time (or time interval) when global warming is predicted to reach a given threshold value would lead to reduced emphasis on the short lived species.

3.4.3. Comparison to other sectors

During the 1990s global CO_2 emissions increased by 13%. Of these emissions road and aviation each experienced a growth in CO_2 emissions of 25%. In Eastern Asia road transport emissions of NO_x and CO_2 doubled during this period (Olivier & Berdowski, 2001). In the European Union, whilst the majority of sectors reduced their greenhouse gas emissions during this period, emissions from the transportation sector increased by ~21%

(EEA, 2003). Nakicenovic et al., (2000) has predicted that the growth in greenhouse gas emission from the global transportation sector will continue and that by 2050 between 30 and 50% of total CO_2 emissions will originate from the transportation sector compared to 2000 levels of 20-25%.

The first comprehensive analysis of the radiative forcing impact due to road, rail, shipping and aviation, using both a historical and futuristic perspective, has been performed by Fuglestvedt et al. (2008). They have found that since pre-industrial times the transportation sector has contributed to more than 20% of the total man-made CO_2 emissions (Figure 10) equating to 15% of the total man-made CO_2 forcing and 30% of the total man-made O_3 forcing. Furthermore their research indicates that the current emissions from the transportation sector are responsible for 17% of the net integrated forcing (100 years) of all current man-made emissions. The dominating effects are from CO_2 and tropospheric O_3 and it is important to note therefore that much of the forcing from the transport sector originates from emissions not included within the Kyoto Protocol (e.g. SO_2, organic carbon and O_3 changes due to precursors such as NO_x, CO and VOCs). As shown in Figure 11 the dominant subsector is road, followed by aviation. In contrast to the other subsectors, shipping emissions result in a negative radiative forcing primarily due to sulphate emissions.

Fuglestvedt et al. (2008) argues that the adoption of 100 years as a time horizon for examining the climate forcing from the transportation sector has implications involving value judgements and that other time horizons should also be considered. For example, Figure 12, from Fuglestvedt et al. (2008), shows the global mean net radiative forcing per sector due to 2000 transport emissions. The results are normalised to the values for road transport for time horizons of 20, 100 and 500 years. The importance of the time horizon is shown in the critical role that short-lived sulphate has on the impact of shipping. In the short to medium timescales the impact of shipping is negative (due to the negative impact of sulphate emissions) whilst over longer timescales the impact becomes positive. A similar argument is applicable to rail. In general the largest scientific uncertainties in calculating the climate impact due to the transportation sector results from the quantification of the indirect effects of aerosols, together with contrails and aviation-induced cirrus. Uncertainties are however also apparent in the estimates of the emissions themselves.

As shown by Fuglestvedt et al. (2008) by only including well mixed mixed greenhouse gases in the Kyoto Protocol the full climate impacts of the transportation sector will not be captured. This is particularly apparent when determining the climate response due to emissions from shipping.

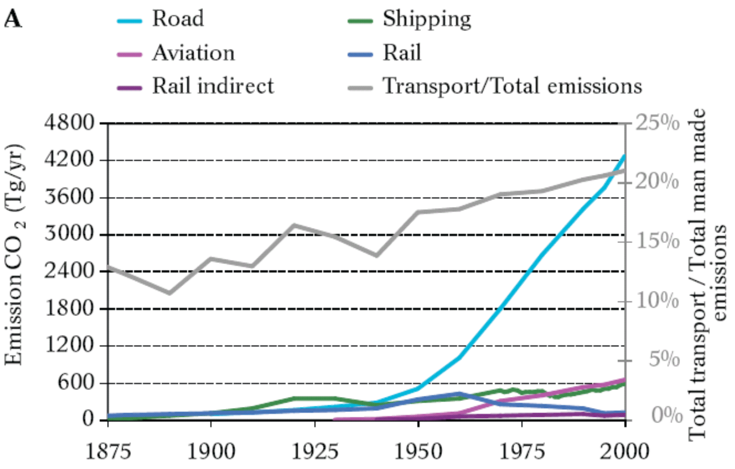

Figure 10: Development of CO_2 emissions from various transport subsectors and the fraction of the total man-made fossil fuel CO_2 emissions – Fuglestvedt et al. (2008).

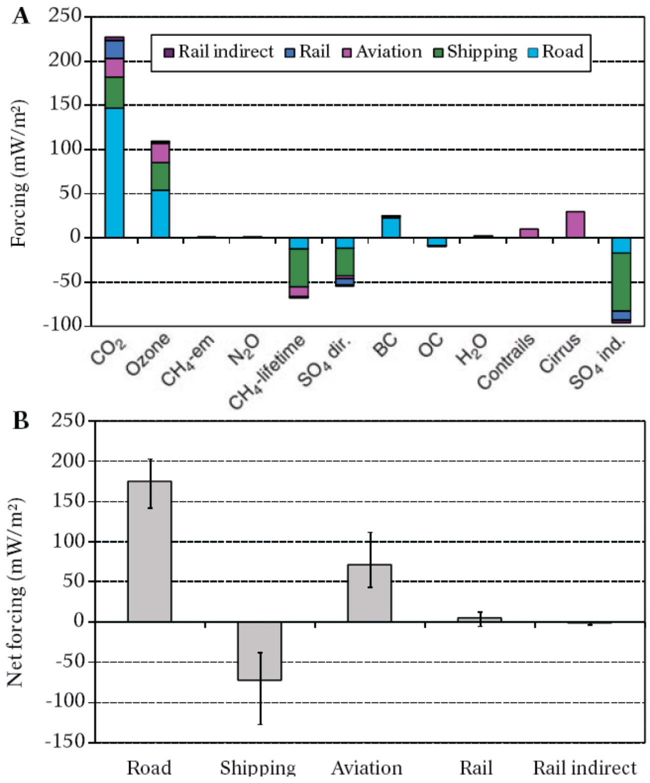

Figure 11: A: Global mean radiative forcing for 2000 due to transport relative to preindustrial times; B: Global mean net radiative forcing – Fuglestvedt et al. (2008).

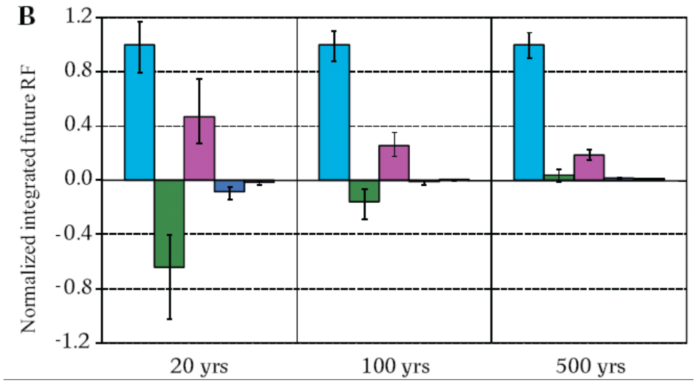

Figure 12: Integrated global mean net radiative forcing per sector due to 2000 transport emissions, normalised to the values for road transport for various time horizons (20, 100 and 500 years) – Fuglestvedt et al. (2008).

4. Prioritization for tackling outstanding issues

A list of recommended priorities for tackling the outstanding issues related to the development and implementation of an appropriate metric for determining aviation's climate impact are given below (Table 6). The scientific limitations, gaps and issues, on which this selection of tasks is based, are discussed in more detail in Sections 3.1 and 3.2. Priority Tasks A relate to research recommendations on general science issues of relevance to metrics (see Section 3.1) whilst Priority Tasks B relate to research recommendations of importance to measurements, analysis and modelling capabilities (see Section 3.2).

In our opinion all of the tasks listed are achievable and will significantly improve our understanding of climate impacts whilst reducing scientific uncertainty. Priority Tasks listed under A are predicted to have a short-term timeline (<5 years). Priority Tasks listed under B are predicted to have varying timelines and practical uses and as such these are explicitly given.

Priority Task	Task	Impact
As1a	Assessment of the literature on alternative approaches to the use of GWPs as a suitable metric of climate change	Improved understanding of issues and whether a different metric is necessary in the future.
As1b	Assessment of the literature on alternative approaches to the use of GWPs as a suitable metric of climate change	Generation of further studies on the political feasibility of various metrics, a critical issue with regard to their implementation.
A1	Efficacy	Diagnosis of the variability in the climate sensitivity parameter.
A2	Confirmation as to the importance of local impacts on global climate change	Impact of local effects on regional/global change – variations with metrics
A3	Assessment of the potential range of impacts diagnosed using a spectrum of metrics and timescales	Improved understanding of the potential impact of aviation under various metrics and timescales
A4	Appropriateness of cancelling negative and positive climate effects	Improved understanding as to whether multiple climate effects can be combined
A5	Appropriateness of pulsed or sustained	Improved understanding of how scenario choice

	emissions of realistic scenarios	leads to different implications of aviation impact
A6	Choice of background scenario	Improved understanding of how background climate change and atmospheric conditions affect metric choice

Priority Task	Task	Impact	Practical Use	Timeline
B1	Improved description of NO_x and NO_y chemistry, sources and sinks	Accurately represent the HO_x – NO_x chemistry of the UTLS region and potential anthropogenic impacts	Model improvement requiring additional observations, laboratory measurements and observations	Long-term (>10 years)
B2	Improved prediction of transport processes throughout the lower atmosphere	Correct determination of the impact of both sub- and supersonic aircraft	Model improvement requiring additional computational resources and long-term observations	Long-term (>10 years)
B3	Model-model intercomparison and model-measurement intercomparison	Improved understanding of the interaction between ozone and methane	Model improvement through comparison and validation	Medium-term (5-10 years)
B4	Impact of a pulse emission of NO_x emitted under different atmospheric conditions and seasons	Improved understanding of climate impact of NO_x emissions under different atmospheric conditions and seasons	Sensitivity analysis	Short-term (<5 years)
B5	Impact of a range of NO_x pulse sizes	Confirmation as to whether the size of the initial positive ozone anomaly, resulting from a pulse emission of NO_x, determines the sign and magnitude of the overall net forcing	Sensitivity analysis	Short-term (<5 years)
B6	Study of impact of cirrus particles on atmospheric composition	The potential role for cirrus particles in the heterogeneous chemistry of the atmosphere	Model investigation requiring additional laboratory studies and in situ observations	Long-term (>10 years)
B7	Study of the processes and radiative effects of contrails and aircraft induced cirrus	Quantification of contrail/cirrus effects	Model investigations with laboratory studies and observations (including in situ and satellite)	Long-term (>10 years)
B8	Forecasting of regions of supersaturation	Development of methods for forecasting supersaturation for use in cloud and contrail prediction	Model investigations with observations	Long-term (>10 years)
B9	Quantification of the full effect of aviation under potential operational and technical procedures	Alternative operational and technical procedures could be adopted by the aviation community if the impact were to be considered as significant	Sensitivity Analysis	Short-term (<5 years)
B10	Long-term observational networks	Long-term observational capability for integrated monitoring of climate gases	Observations	Long-term (>10 years)

Table 6. Prioirization of Research Tasks

5. Recommendations for best use of current tools for modeling and data analysis

5.1. Options

Currently, when determining any climate impact, a choice exists between:

- simple analytical models such as GWPs and GTPs;
- models of intermediate complexity that calculate induced temperature change for various scenarios (in the case of aviation those given by Lim et al., 2007; Sausen and Schumann, 2000; Wit et al., 2005); and
- the option of running integrations in complex coupled climate models.

The range of possible metric options are shown in Table 7, and provide a basis for the best available options and approaches with which to quantify the climate impact under varying scenarios.

It should be noted that it is important to consider aviation climate issues within the wider context of the political landscape, air quality concerns and other transport sectors (Section 3.4). There remains however issues about which emissions and factors should be included in policy decisions and whether to have separate policies for different emissions (CO_2 and NO_x) or one unified metric, such as the GWP. A multiple-agent metric will likely have more cost-effective benefit when applied, provided it is scientifically robust (see Section 3.4). These aspects we feel are still very much an open question. The inclusion of short-lived climate gases in any climate policy will require scientific robustness and therefore a substantial degree of model independence. The results of Berntsen et al. (2005) indicate that short-lived species could be included in future climate policies however their level of credibility will remain less than that of the long-lived species.

Our recommended approach for the best use of current tools involves simple metrics only (GWP and GTP) and including in these all forcing factors that are relatively well quantified (currently excluding the role of aviation induced cirrus). Since likely future policy will be directed towards reductions by a particular target date, we recommend the adoption of ASGTP(H), limited probably to a target date around 2060, as this time horizon features in draft European union policy and UNFCC- Bali discussions. The reasons for this selection are given in the following subsection (5.2).

Specific modeling integrations should be performed on an individual basis dependent upon the scientific and/or political question that is to be addressed. If, for example, we are interested in the global impact of a tripling in the aviation system capacity (and as such a related doubling in aviation emissions) then we recommend that, with input from a range of global atmospheric models, the metric ASGTP(2060) be applied for comparison with other scenarios (including alternative transportation options and future climates). We refer to other SSWPs theme areas for recommendations on the choice of atmospheric models, emissions and background conditions.

Metric	Usage and advantages	Disadvantages
All	Combining climate impact of more than one emission source in a quantifiable way	Difficulty in quantifying many effects, given current scientific understanding Conceptual difficulty in handling the compensation between opposing forcings on a global level when they do not compensate locally
RF(present), ΔT(present)	Gives impact of all current and past emissions on RF and ΔT at the present. Includes "responsibility" for past emissions	Temperature metrics add complexity and uncertainty to calculations, as the climate sensitivity parameter is poorly quantified. Nothing can be done now about past emissions
RF(future), ΔT(future)	Gives impact of all current and past emissions on RF and ΔT at some future date. Could also include scenarios of emissions between present day and future date	As above, but with additional uncertainty due to scenario
RF or ΔT due to emissions in one year	Use of PGTP(H) (or similar metric for forcing) to give impact of current emissions on temperature at some time in the future	Choice of time horizon has much stronger effect on results than is the case for GWPs, and could be manipulated to suit "world view"
RF(target), ΔT(target)	Similar to above, but could be used if the policy were to aim to restrict the contribution to RF or ΔT at some future target date, it would say how much current emissions are contributing to that target. Impact of short-lived emissions would grow as target time is approached	As above. Additional difficulties in choosing the target date. Some argue that the rate of change of temperature is as important as the actual change in temperature
Time integrated RF due to emissions in one year	Use of Standard GWP(H) would characterise the impact of current emissions in a manner that is consistent with the Kyoto Protocol and the accepted method of achieving carbon equivalence by most other sectors. Choice of H=100 years would be fully consistent with Kyoto, but could be presented for range of H (e.g. 20, 100, 500 years)	Strong negative comments made about use of GWP for aviation, in high profile places, notably IPCC (1999). These would need countering when presented
Sustained GWP(H) and GTP(H)	Sustained versions of the pulse GWP and GTP, in which the effect at time H is considered if the current emissions are sustained between now and H	Difficulty in explaining usage and the assumption of constant future emissions
Economic impact metrics	Monetary unit based on global temperature or local climate effects, (precip, storms etc.); also could be based on impacts (flooding, drought etc) or livelihood change indices. Has advantage of being closer to real world effects.	Hugely uncertain. Combines uncertainties. In regional climate modelling and socioeconomic modelling.

Table 7: Metric options

5.2. Supporting rationale

Considering aviation's effects within complex climate models is firstly problematic because aviation is only a minor perturbation within the context of natural variability. The advantage of using these models is that they are able to capture physical interactions. However, physical processes such as aviation induced cirrus are not understood and to include simple empirical parameterizations within climate models would be unnecessarily complicated (we would be building in interactions we didn't understand). Therefore we conclude that their use in a metric context brings no clear benefit.

Intermediate models give global temperature evolution and allow the user to explore mitigation options and give a suggestion of climate impact. However, we argue against them for giving a misleading confidence to the user. Because they show temperature evolution over the next 100 years, people may interpret these as reality when in fact they are have many uncertainties: quantification of forcing and efficacy, uncertainty in background scenario and uncertainty in climate response, such as ocean heat up take. We therefore do not endorse them. This is especially true when making such models publicly available for end users to experiment with, as end users may not understand their limitations or valid ranges of applicability.

The choice of a simple analytical model to determine the sustained emission GTP is based on its transparency and ease of use (only a small number of input parameters are required in the calculation). The derivation of GTP is robust to simplifications and key uncertainties, and the unambiguous interpretation and increased relevance, due to its progression down the cause-effect chain of climate impacts, makes it a valuable metric for policy makers.

We recommend that all metrics be applied at a globally integrated level as there is too much uncertainty to distinguish either global differences in response from similar emissions in different regions or to determine the local response to global emissions. Therefore even if Asian NOx emissions are worse than European NOx emissions in terms of their climate impact, we believe that uncertainties are too large to be able to quantify these differences adequately within a policy framework

Our recommendation that aviation induced cirrus should be excluded from both GWP and GTP metrics is due to the current lack of knowledge regarding the quantification of the full (both direct and indirect) impact due to this effect. Line shaped contrails, although not related to a particular emission can be easily associated with distance flown or emissions for CO2. As in this report, associating their emissions with that of CO2 enables simple comparison with the effects of other factors. Note that such an association is only valid on a globally-integrated sense due to the dependence of contrail formation on background conditions – this again reinforces the use of global metrics, compared to local ones. We particularly emphasize, both for contrail and for other factors, that uncertainties should be quoted whenever a metric is deployed.

The choice of time horizon is not just a science issue. Although the Kyoto protocol adopts 100 a 100 year time horizon, current policy discussion centres on shorter time scales. A 50 year timescale seems appropriate as it is still primarily concerned with addressing long-term climate change, but within a typical human lifetime. At this timescale shorter lived emissions still play a significant role

5.3. How to best integrate best available options?

We recommend continued science studies to reduce uncertainties where achievable, and the use of simple metrics. We recommend quoting ranges for a number of metrics, as different metrics give different indications of importance. This also prevents metrics being deliberately chosen to advocate particular policy choices. Development of our understanding of the atmosphere and computational power should eventually enable sophisticated coupled climate models to be used to explore metrics of aviations impact. Approaches of integration of air quality and climate change requires incorporation into economic models of climate impact (as in the Stern, 2007 review). Assessing the available options here is beyond the scope of our expertise and would require input from economists with knowledge of costing climate mitigation options who would also ideally have a knowledge of the aviation industry.

We finally note that metric choice is very much a policy issue and people from a range of disciplines including policy makers should ultimately decide on the most appropriate metric choice. Time horizon etc. cannot be chosen on purely physical science grounds.

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