Meteorologische Zeitschrift, Vol. **17**, No. 2, 157-172 (April 2008)

Article

Assessing the impact of aviation on climate

KAREN MARAIS[1], STEPHEN P. LUKACHKO[2], MINA JUN[2], ANUJA MAHASHABDE[2] and IAN A. WAITZ[*2]

[1]Department of Industrial Engineering, University of Stellenbosch, South Africa
[2]Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, USA

(Manuscript received November 23, 2006; in revised form April 10, 2007; accepted May 13, 2007)

Abstract

We present an assessment of the marginal climate impacts of new aviation activities. We use impulse response functions derived from carbon-cycle and atmospheric models to estimate changes in surface temperature for various aviation impacts (CO_2, NO_x on methane, NO_x on ozone, sulfates, soot, and contrails/induced cirrus). We use different damage functions and discount rates to explore health, welfare and ecological costs for a range of assumptions and scenarios. Since uncertainty is high regarding many aviation effects, we explicitly capture some uncertainty by representing several model parameters as probabilistic distributions. The uncertainties are then propagated using Monte Carlo analysis to derive estimates for the impact of these uncertainties on the marginal future climate impacts. Our goal is to provide a framework that will communicate the potential impacts of aviation on climate change under different scenarios and assumptions, and that will allow decision-makers to compare these potential impacts to other aviation environmental impacts. We present results to describe the influence of parametric uncertainties, scenarios, and assumptions for valuation on the expected marginal future costs of aviation impacts. Estimates of the change in global average surface temperature due to aviation are most sensitive to changes in climate sensitivity, the radiative forcing attributed to short-lived effects (in particular those related to contrails and aviation-induced cirrus), and the choice of emissions scenario. Estimates of marginal future costs of aviation are most sensitive to assumptions regarding the discount rate, followed by assumptions regarding climate sensitivity, and the choice of emissions scenario.

Zusammenfassung

Es werden die Auswirkungen durch neue Luftfahrtaktivitäten auf das Klima präsentiert und bewertet. Hierbei wird von Impuls-Reaktions-Funktionen (impulse response functions) aus Kohlenstoff-Zyklen und atmosphärischen Modellen zur Schätzung der Veränderungen in der Oberflächentemperatur für die verschiedenen Auswirkungen der Luftfahrt (CO_2, NO_x auf Methan, NO_x auf Ozon, Sulfate, Ruß, Kondensstreifen von/-induzierter Zirrus) Gebrauch gemacht. Für eine Reihe von Annahmen und Szenarien werden die Kosten für Gesundheit, Wohlfahrt und Ökologie mittels Schadensfunktionen und Abschlagsätzen analysiert. Zur Abbildung der Unsicherheit der Effekte in der Luftfahrt wurden mehrere Parameter als Wahrscheinlichkeitsverteilung modelliert. Durch Monte-Carlo-Analyse werden die Auswirkungen auf das zukünftige Klima geschätzt. Ziel ist es einen Rahmen zu schaffen, der potenzielle Auswirkungen einzelner Entscheidungen in der Luftfahrt auf den Klimawandel aufzeigt. Eine konkrete Unterstützung von Entscheidungsträgern durch Szenarien ist angestrebt. Es werden Ergebnisse präsentiert, die den Einfluss der parametrischen Unsicherheiten, Szenarien und Annahmen beschreiben sowie die Bewertungsgrundlage der zukünftig erwarteten marginalen Kosten der Luftverkehrseinwirkung bilden. Schätzungen über die Änderungen der durchschnittlichen globalen Oberflächentemperatur durch die Luftfahrt sind sehr empfindlich auf Veränderungen der klimatischen Sensitivität, auf Strahlungseigenschaften und auf kurzzeitige Effekte (vor allem im Zusammenhang mit Kondensstreifen und durch die Luftfahrt induziertem Zirrus), und auf die Wahl des Emissions-Szenarios. Schätzungen der zukünftigen marginalen Kosten der Luftfahrt sind besonders störanfällig bezüglich für den Diskontsatz, gefolgt von den Annahmen für die Klima-Sensitivität, und die Wahl des Emissions-Szenarios.

1 Introduction

There are a variety of potentially important trade-offs for aviation and climate change. Questions include how to evaluate interdependencies among local air quality, noise and climate impacts, and how best to evaluate the importance of short-lived climate effects versus CO_2 when considering how to include aviation in emissions trading. To select environmental policies that balance society's economic and environmental needs, policymakers wish to assess the full impact of candidate policies, while also accounting for potential interdependencies. It is also necessary to provide guidance to manufacturers and airlines as they seek to balance a variety of environmental, safety, and performance objectives. This is particularly important because of the capital-intensive nature of the industry ($\sim 1\text{x}10^{10}$ U.S. dollars for a new airplane development effort) and because of the long time-scales for development and use (airplane

[*]Corresponding author: Ian A. Waitz, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, 02139, USA, e-mail: iaw@mit.edu

0941-2948/2008/0274 $ 7.20

DOI: 10.1127/0941-2948/2008/0274

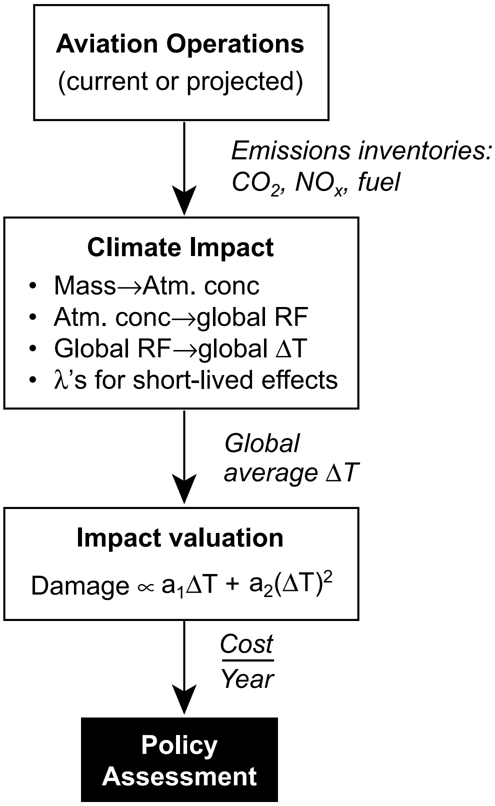

Figure 1: Overview of modeling approach.

technology under development today may still be flying 50 years from now).

In these types of complex decision-making environments, policy-makers need a "shared conception of what is at stake in the choice of one level of effort or another, and a common terminology for incorporating these considerations into international negotiations and domestic decision-making" (JACOBY, 2004). One way of presenting benefits and costs of policies in common terms is to express them in monetary terms, in a process referred to as benefit-cost analysis (BCA). BCA of environmental impacts has some theoretical and practical limitations when used as the sole basis for decision-making, particularly in cases of high complexity, high uncertainty and where there are different conceptions of the value of non-market goods among stakeholders (cf. ELGHALI, 2002). Nevertheless, BCA is regarded by many as a valuable component of environmental policy decision-making processes (e.g., FUGLESTVEDT et al., 2003; PEARCE, 2003); indeed it is a required component of environmental policy analysis within many government agencies around the world.

We present a flexible, simplified, probabilistic framework to estimate the marginal climate impacts of new aviation activities. The model is based on the needs of the policy-making community and is easily configurable to different physical and economic models of climate change and its impacts. We recognize that it is not possible to predict with confidence the costs and benefits of climate change over hundreds of years. However, we present the framework as a means for exploring the potential consequences of aviation activity for a range of different scientific and economic assumptions (cf. SCHNEIDER et al., 2000, and POPPER, 2006). Importantly, we attempt to explicitly represent the impacts that the uncertainties in some key scientific parameters have on the estimated costs and benefits.

The underlying concepts we employ are not new – we borrow heavily from prior work on climate impacts of anthropogenic activities, including aviation. We use different impulse response functions derived from carbon-cycle and atmospheric models to estimate changes in globally-averaged surface temperature for various aviation impacts (CO_2, NO_x on methane, NO_x on ozone, water, sulfates, soot, and contrails/ aviation-induced cirrus). We use different damage functions and discount rates to explore the health, welfare and ecological costs for a range of scenarios and assumptions. Since uncertainty is high regarding many aviation effects, we explicitly capture some uncertainty by representing several model parameters as probabilistic distributions. The uncertainties are then propagated using Monte Carlo analysis to derive estimates for the impact of these uncertainties on the marginal future climate costs.

The remainder of this paper is organized as follows. Section 2 presents our methods for assessing the impact of aviation on climate. Section 3 presents results, and Section 4 concludes the paper.

2 Method

Figure 1 illustrates our modeling approach, which follows the approaches of HASSELMANN et al. (1997), SAUSEN and SCHUMANN (2000), FUGLESTVEDT et al. (2003), SHINE et al. (2005) and NORDHAUS and BOYER (2000). We begin with estimates of current and future emissions inventories both for aviation and for all anthropogenic sources. We then determine the potential change in globally-averaged surface temperature using impulse response functions derived from carbon-cycle and coupled atmosphere and ocean general circulation models (GCMs). Next, we calculate several different indicators, namely, change in global average surface temperature, percentage impact on gross domestic product (GDP), and net present value of future impacts of climate change (see Section 2.2 for a discussion of net present value). We consider the impacts of emissions over the entire period during which significant effects persist – capturing the full time horizon for the physical impacts (against which economic assumptions about valuing the long-term impacts can be explicitly applied). In the case of CO_2 this period is several centuries.

2.1 Temperature change

We model several different mechanisms through which aviation emissions affect climate. The impact of CO_2 on climate is modeled using linearized impulse response functions derived from carbon-cycle and general circulation models (HOOSS et al., 2001; HASSELMANN et al. (1993); HASSELMANN et al. (1997); CUBASCh et al. (1992); PLATTNER et al., 2001; JOOS et al., 2001) following the approach of SAUSEN and SCHUMANN (2000). To explore the influence of climate sensitivity, we also use an impulse response function from the Bern carbon-cycle model (PLATTNER et al., 2001; JOOS et al., 2001) with a simplified energy balance model of the atmosphere following SHINE et al. (2005).

The impact of carbon dioxide on the atmosphere is non-linear: additional units of carbon dioxide cause progressively less radiative forcing[1]. We therefore determine the impact of aviation CO_2 over time by calculating the impact of all anthropogenic sources and subtracting the impact of all anthropogenic sources excluding aviation:

$$\begin{aligned} &\text{Impact}\,(CO_2 \text{ aviation}) = \\ &\text{Impact}\,(CO_2 \text{ anthropogenic}) - \\ &\text{Impact}\,(CO_2 \text{ anthropogenic} - \text{aviation}) \end{aligned} \tag{2.1}$$

Since temperature change and hence impact of climate change are calculated with respect to background scenarios, it is important to ensure that the levels of aviation activity are consistent with the background scenarios. In this paper, we use IS92a for the baseline background scenario but also explore the influence of alternative background emissions levels using the IS92c and IS92e scenarios (see Section 3.1).

The change in atmospheric CO_2 concentration at time t' due to anthropogenic emissions is given by:

$$\begin{aligned} G_C(t') &= \sum_{j=1}^{n_j} \alpha_j e^{-(t')/\tau_j} \\ \Delta X_{CO_2}(t') &= \int_{t_0}^{t'} Q_{CO_2}(t'') \cdot G_C(t'-t'')dt'' \\ &\approx \sum_{n=0}^{N-1} Q_{CO_2}(t_0+n\Delta t) \cdot G_C(t'-t_0-n\Delta t) \cdot \Delta t \\ N &= (t'-t_0)/\Delta t \end{aligned} \tag{2.2}$$

where $G_C(t')$ is the carbon cycle impulse response function, $Q(t'')$ is the mass of CO_2 emitted from anthropogenic sources during one year of activity, $\Delta X(t')$ is the corresponding change in atmospheric CO_2 concentration and Δt is one year.

[1]Damage from climate change may also be non-linear, but in this case it is expected that additional warming may cause more damage than initial warming.

The resulting normalized radiative forcing, $RF^*_{CO_2}$ at time t' is associated with CO_2 concentration at time t' by assuming a logarithmic dependence (IPCC, 1995):

$$RF^*_{CO_2}(t') = \log_2\left(\frac{X_{CO_2(present)} + \Delta X_{CO_2}(t')}{X_{CO_2(1750)}}\right) \tag{2.3}$$

where the atmospheric concentration of CO_2 in the year 1750 is taken as 278 ppm. The RF is normalized such that $RF^*_{CO_2} = 1$ for a doubling of CO_2 concentrations relative to 1750.

Finally, we determine the global average temperature change, $\Delta T_{CO_2}(t)$, at time t resulting from radiative forcing $RF(t')$:

$$\begin{aligned} G_T(t) &= \sum_{i=1}^{n_i} \alpha_i e^{-t/\tau_i} \\ \Delta T_{CO_2}(t) &= \int_{t_0}^{t} RF^*_{CO_2}(t') \cdot G_T(t-t')\,dt' \\ &\approx \sum_{n=0}^{N-1} RF^*_{CO_2}(t_0+n\Delta t) \cdot G_T(t-t_0-n\Delta t) \cdot \Delta t \\ N &= (t-t_0)/\Delta t \end{aligned} \tag{2.4}$$

where $G_T(t)$ is the temperature response model and Δt is again taken as one year.

Climate sensitivity is uncertain and estimates of it differ significantly among different atmospheric models. Ideally we would like to test impulse response functions derived from GCMs that reflect a range of climate sensitivities. However, such a wide range of impulse response functions is not available in the literature. We therefore assess the impact of this parameter using a simple energy balance model that relates climate sensitivity to the temperature response (SHINE et al., 2005). Although this approach has lower fidelity than the impulse response functions derived from more complex models, it allows us to estimate the importance of climate sensitivity to our assessments of the impact of aviation on climate. The temperature response based on this approach is given by:

$$\begin{aligned} &\Delta T(t) = \tfrac{1}{C}\int_{t_0}^{t} \Delta F(t') \exp\left(\tfrac{t'-t}{\lambda^* C}\right) dt' \\ &\lambda^* = \tfrac{\lambda}{RF_{2XCO_2}} \\ &\Delta F(t') = RF * RF_{2XCO_2} \\ &\tau = \lambda^* C \end{aligned} \tag{2.5}$$

where, C (4.2x10^8 J/Km^2) is the ocean heat capacity for a global ocean mixed layer of 100 m depth and RF_{2XCO_2}(3.7 W/m^2 (IPCC, 2001)), is the RF for a doubling of CO_2 relative to pre-industrial levels. λ is the climate sensitivity and is input as the climate sensitivity parameter, λ^*[K/Wm^{-2}], defined in Equation (2.5). RF^* is the normalized radiative forcing for the different effects. τ[years] is the time constant of the climate system and is related to the climate sensitivity parameter, λ^*.

For the short-lived effects (i.e., effects assumed to have lifetimes of one year or less, including the immediate effect of NO_x on ozone, contrails and aviation induced cirrus, water, sulfates and soot) we assume the radiative forcing is only active in the year of the emissions and then determine the temperature change associated with each effect as for CO_2. Following SAUSEN and SCHUMANN (2000), we represent aviation short-lived effects by scaling the normalized radiative forcing for each effect relative to CO_2:

$$RF^*_{short_j}(t_0) = \frac{\lambda_{short_j}}{\lambda_{CO_2}} \cdot \frac{RF^{ref}_{short_j}}{RF_{2XCO_2}} \cdot \frac{Q_{short_j}(t_0)}{Q^{ref}_{short_j}} \qquad (2.6)$$

where the λ's are the sensitivities for each effect, the *RF*s are the reference radiative forcing values for each effect, $RF_{2XCO_2} = 3.7$ W/m^2, is the radiative forcing for a doubling of atmospheric CO_2 concentration relative to the pre-industrial level, Q_{short} is the emissions quantity for each effect, and $Q_{short,ref}$ is the reference emissions quantity corresponding to $RF_{short,ref}$. The ratio $\lambda_{short}/\lambda_{CO_2}$ is the efficacy for a given effect. For most of the results we present in this paper, we have set the baseline values of the efficacies to unity, but we also assess the impacts of non-unity sensitivities using results from HANSEN et al. (2005) as shown in Table 1. The most recent estimates of reference radiative forcings for aviation effects are for the year 2000, as presented by SAUSEN et al. (2005), and are also shown in Table 1[2]. For the ozone impact, we assume that the emissions quantity is proportional to the NO_x inventory. For all other short-lived impacts we assume that the emissions quantity is proportional to the fuel burn inventory. In the case of contrail and cirrus formation this assumption may not be valid beyond the first order, as contrail and cirrus formation is not only dependent on distance traveled, but also on other factors such as flight altitude and weather conditions.

[2]The triangular distributions for the RF values given in Table 1 were defined such that the peak corresponds to the values given by SAUSEN et al. (2005). IPCC (1999) provides 67 % confidence intervals for the RF values, but insufficient information about the shape of the distribution to allow these intervals to be used as anything other than a guide in defining our triangular distributions. Therefore, we set the limits of our triangular distributions to fall close to, but outside of, the 67 % confidence intervals given by IPCC (1999). There are two exceptions to this: for contrails we reduced the limits of our distribution relative to IPCC (1999) to reflect the lower overall impact estimates reported recently (e.g. SAUSEN et al. (2005)); and for aviation-induced cirrus cloudiness we used the range given in SAUSEN et al. (2005) to define the limits of the distribution, with the peak set at 30.0 mW/m^2. Our distributions should not be taken as definitive, but rather as approximate estimates of the uncertainties in these parameters.

Table 1: Climate forcing reference radiative forcing and distributions for year 2000.

Emission	Reference RF [mW/m^2]	Triangular Distribution Limits	Efficacies	
			Baseline estimate	HANSEN et al., (2005)
NO_x-O_3	21.9	0; 50	1	0.82
NO_x-CH_4	–10.4	N/A	1	N/A
H_20	2.0	0; 6.0	1	not given
Sulfates	–3.5	–10; 0	1	1.09
Soot	2.5	0; 10	1	0.78
Contrails	10.0	0; 30	1	0.59
Cirrus	30.0	0; 80	1	not given

We use different methods to model two longer time-scale impacts of NO_x: the decrease in methane lifetime resulting from the presence ofNO_x, and the resulting small decrease in ozone over the same time period. In doing so, we focus on the primary mode NO_x-CH_4-O_3 interactions and do not explicitly consider changes due to other ozone precursors such as CO and VOCs (cf. IPCC, 2001 and IPCC, 1999). The first step in modeling the methane impact is to determine the initial radiative forcing. In this context it is not appropriate to use the reference radiative forcing values for methane as given in the IPCC (2001) or SAUSEN et al. (2005) because these values represent the radiative forcing for changes in methane due to accumulated historical aviation emissions. We wish to model the marginal impacts of new aviation operations. Therefore, we derive the initial value for the methane RF by scaling the SAUSEN et al. (2005) short-lived ozone values using 100-year time integrated radiative forcing results from STEVENSON et al. (2004,) as shown in Equation (2.7). STEVENSON et al. (2004) present integrated radiative forcing in mW-yr/m$_2$, which indicates radiative forcing summed over a 100-year time frame and is analogous to the concept of the Absolute Global Warming Potential described in the IPCC TAR (2001).

$$\begin{aligned}
&\frac{\int_0^{100} RF_{ozone-short}(t)\,dt}{\int_0^{100} RF^{ref}_{methane}(t_0)\,e^{-t/\tau_{methane}}\,dt} = \frac{RFyr^{Stevenson}_{ozone-short}}{RFyr^{Stevenson}_{methane}} \\
&\int_0^{100} RF_{ozone-short}(t)\,dt \approx RF^{ref}_{ozone} \cdot 1\text{yr} \\
&RF^{ref}_{methane} = \frac{RFyr^{Stevenson}_{methane}}{RFyr^{Stevenson}_{ozone-short}} \cdot \frac{RF^{ref}_{ozone} \cdot 1yr}{\tau_{methane}}
\end{aligned} \qquad (2.7)$$

The mean 100-year *RF-yr* values from STEVENSON et al. (2004) are taken to be 5.06 mW-yr/m^2 for ozone and –4.00 mW-yr/m^2 for methane. We use the mean *e*-folding time for methane, $\tau_{methane}$, of 11.07 yrs as defined by STEVENSON et al. (2004, Table 2) and the reference ozone RF from SAUSEN et al. (2005). This approach eliminates the influence of historical aviation emissions and reflects the future methane impact from NO_x emissions levels for a given aviation scenario. Given the methane RF over time, we proceed in a manner analogous to that used to calculate the temperature impact of CO_2.

We follow a similar procedure to calculate the RF for the longer-term NO_x-ozone cooling impact. In this case we calculate the initial ozone RF based on the same approach as Equation (2.7), using the ozone RF values from SAUSEN et al. (2005) and STEVENSON et al. (2004). We then allow the ozone RF to decay using an exponential function with the methane *e*-folding time of about 11 years.

2.2 Climate impact valuation

Next we describe our methods to assess the economic impact of a change in globally-averaged surface temperature. Benefit-cost analyses of climate change under different future scenarios and policies have been proposed by several authors, notably NORDHAUS and BOYER (2000), MENDELSOHN et al. (2000), and TOL (2002a, b). Economic assessments of all environment-related benefits have limitations, arising from the complexity of the problem and the difficulties of valuing impacts not traditionally expressed in monetary terms (see, e.g., SCHNEIDER, 1997). However, these methods offer a basis for comparing environmental impact mitigation policies, provided that one is clear on the limitations, assumptions, and uncertainties. Commenting on the limitations of BCA, Working Group 2 of the IPCC Third Assessment notes: "However, it is still better to get at least the measurable components right and complement them with a combination of judgments on hard-to-measure items and sensitivity tests to assess their implications than to abandon the whole method simply because it does not get everything perfect" (IPCC WG2, 2001).

General damage function forms have been proposed by several authors over the past two decades. In this paper we use two damage function formulations, a linear damage potential (LDP) that assumes damage is proportional to temperature change (and can therefore be measured in Kelvin if we set the proportionality constant to one), and one derived by NORDHAUS and BOYER (2000). Nordhaus and Boyer based their assessment of damages on valuations of climate impact in six major categories: agriculture, sea level rise, health, human settlements and ecosystems, other market sections affected by climate change, and non-market impacts. They also account for the possibility of catastrophic climate change. The constants in the damage function are calibrated to estimate damage as a percentage of the gross domestic product of a particular region. Thus, the yearly damage from climate change for a region k is given by a quadratic relationship of the form of Equation (2.8):

$$D_k(t) = a_{1,k}\Delta T_{1900}(t) + a_{2,k}\Delta T_{1900}(t)^2 \qquad (2.8)$$

Where $D_k(t)$ is in %GDP, ΔT_{1900} is the temperature increase in Kelvin since 1900, and $a_1 = 0.0045$, $a_2 = 0.0035$ for global average impact. The coefficients a_1 and a_2 have units %GDP change per Kelvin and per Kelvin-squared, respectively. The Nordhaus and Boyer approach to damage valuation has been criticized for the simplifying assumptions it contains, such as excluding non-market impacts (e.g., loss of natural beauty and extinction of species). However, these types of limitations are a feature of most current approaches to damage valuation. It is generally recognized that the Nordhaus and Boyer study is the most extensive and detailed to date (see, e.g., YOHE, 2002). It is also notable that the damage estimates from Nordhaus and Boyer are generally larger than those from other studies (for a comparison, see IPCC WG2 Report, 2001, Table 19-4).

Since the damage function is non-linear, we calculate damage due to individual effects in two steps. First, we calculate the damage due to all anthropogenic impacts. Next, we calculate the damage due to all anthropogenic impacts, less the impact in which we are interested. The damage for a particular impact is then given by:

$$\begin{aligned}&\text{Damage}\left(\text{effect}_\text{i}\right) = \\ &\text{Damage}\left(\text{all anthropogenic effects}\right) - \\ &\text{Damage}\left(\text{all anthropogenic effects} - \text{effect}_\text{i}\right)\end{aligned} \qquad (2.9)$$

The final step in our analysis is to discount the calculated damage costs and determine the net present value (NPV) of the climate impact. Discounting is used to express future value streams in present monetary terms. A common example is to consider that a monetary unit today is worth more than that same unit in the future because it could be invested and generate returns. We can express this concept as follows, where r is the discount rate per time unit:

$$Value(t) = \tfrac{Value(t+1)}{1+r} \quad 0 < r < 1 \qquad (2.10)$$

When we consider flows of social goods over long time periods, as must be done with climate impacts, discounting is used to express social values about the distribution of welfare among generations, and about the relative ability of different generations to bear costs. In this context, there are three basic types of discounting: *pure time preference*, *growth*, and *goods discounting* (NORDHAUS, 1997). *Pure time preference* is used to reflect different scenarios for how we may value our welfare over the welfare of future generations. *Growth discounting* is used to show how we may balance the burden for addressing costs among generations that have different levels of wealth. For example, if real incomes are anticipated to increase over time (as they have historically), future generations will have greater disposable income with which to address climate costs. *Goods discounting* combines time and growth discounting into the *social rate of time preference*, r, and is the rate used to discount future climate impacts. These concepts are related mathematically by the Ramsey rule, which is based on the assumption that policies should be designed to improve the living standards of both current and future generations (see also, GROOM et al., 2005):

$$r = \rho + \theta \cdot g \tag{2.11}$$

where ρ is the rate of pure time preference, g is the growth rate of per capita consumption, and θ is the elasticity of the marginal utility of consumption. θ measures the rate of change of utility derived from an extra unit of consumption as incomes increase (GUO et al., 2006)[3]. A high goods discount rate (r) can be obtained with a high rate of pure time preference (ρ) or a high growth discount rate (g). The net present value of a flow of value over time can then be expressed as:

$$NPV\,(n) = \sum_{n'=n_0}^{n} \frac{Value\,(n'-n_0)}{(1+r)^{n'-n_0}} \tag{2.12}$$

Where n is a positive integer representing the period over which the discount rate r is applied. In our case, n is in years, and r is the annual discount rate.

Ethical concerns about discounting the welfare of future generations can be addressed by setting the rate of pure time preference to zero (cf. GROOM et al., 2005; LIND, 1982; NORDHAUS, 1997; CLINE, 2004). The growth discount rate may still be set high because capital is scarce (thus increasing the value of present incomes relative to future incomes), or to reflect an assumption that incomes will grow rapidly. Or the growth discount rate may be set low because capital is abundant, or incomes are growing slowly.

While the use of discounting in valuing climate impacts remains contentious (e.g., HEAL, 1997; NORDHAUS, 1997), net present values capture the impact of per capita income growth and reflect the way that individuals typically make decisions on a daily basis. Different governments recommend different approaches to discounting and it is standard practice in policy-making to present the analysis results under several alternative discount rates and/or discounting methods.

2.3 Limitations

Before proceeding to a discussion of results, we will note some important limitations of our modeling methods. First, we use globally-averaged parameters (emissions inventories, radiative forcing and surface temperature change) to represent the physical impacts of aviation on climate. However, it is well understood that radiative forcing due to contrails, aviation-induced cirrus cloudiness, and production of ozone via NO_x will occur in regions where aircraft fly – predominantly the northern hemisphere. Modeling such radiative forcing as globally-uniform, and assuming that it may be simply superposed with radiative forcing due to well-mixed gases such as CO_2 and methane, may inaccurately represent the more complex response of the climate to spatially non-homogeneous forcing. Second, the carbon cycle models that we use are dependent on background CO_2 concentrations and neglect carbon cycle feedbacks. Third, the climate models we use were derived from GCM calculations, but the calculations were not specifically for a pulse. The extent to which the models accurately represent the response to a pulse is thus uncertain. Fourth, there are some mechanisms for which the science is too immature to provide a basis for including them in our model. The effect of aircraft soot and sulfur emissions on the properties of clouds is one such area. Some may argue the same is true for aviation-induced cirrus cloudiness; however, we have included it in our analysis, but with the highest variance assumed of any of the effects. Finally, although we attempt to explicitly represent the uncertainty in several important parameters, and to quantify the effects of this uncertainty on our results, we have not captured all sources for uncertainty.

Table 2: Baseline values.

Input	Values
Anthropogenic emissions	IS92a
Aviation emissions impulse	SAGE2003
Aviation scenario	SAGE2003, NASA2015, FESG Fa1, extrapolated from 2050 to 2100 with 1 % growth
GDP	IS92a
Carbon cycle impulse response models	Bern Carbon Cycle (PLATTNER et al., 2001, JOOS et al. 2001)
Temperature impulse response models	SHINE et al. (2005)
Climate sensitivity	2.5K for CO_2 doubling
Short-lived radiative forcing	See Table 1, reference RF values (column 2)
Short-lived efficacy	All set to unity
Methane lifetime	11.07 years
Reference temperature change	0.6 K
Damage function	ΔT, NORDHAUS and BOYER (2000) damage function
Discount rate	3.5 %

[3]Values of θ is a measure of the curvature of the utility function, and is equivalent to the coefficient of relative risk aversion. The literature suggests that this value is around unity [GUO et al., 2006], which means that an extra dollar to a generation with twice the consumption of the current one will only provide that generation with half the utility. Values of higher than unity imply that the future generation would derive less than half the utility.

3 Results

We begin in Section 3.1 by presenting baseline results for one year of aviation activity, and for a 100 year aviation scenario based on FESG scenario Fa1 (CAEP/4-FESG, 1998). Table 2 shows the baseline parameters. For the single year case we use emissions inventory data for 2003 from the FAA's Aviation Environmental Design Tool, System for Assessing Aviation's Global Emissions (AEDT/SAGE) (FAA, 2005a, b). For scenario inputs, we use SAGE 2003 data as a starting point, NASA estimates for 2015 (see IPCC, 2001a) and then follow FESG scenarios Fa1, Fc1, and Fe1 to 2050 (CAEP/4-FESG, 1998), with 1 % growth thereafter up to 2100 (following Sausen and SCHUMANN, 2000). Background CO_2 emissions and GDP values are based on IS92 scenarios a, c, and e (PEPPER et al., 2005). For IS92c we extrapolated emissions data by assuming that emissions after 2100 remain constant in order to avoid negative emissions and GDPs. We use the IS92 scenarios because these scenarios are currently the only public-source scenarios for which matching and consistent aviation emissions scenarios (FESG) are available.

In Section 3.2 we present the results of sensitivity studies and scenario analyses. For these results, we represent the effects of scientific uncertainty by specifying some parameters as probabilistic distributions. We use Monte Carlo analysis, sampling randomly from these distributions until a converged output distribution is obtained. We do this for the value of CO_2 RF for a doubling of the atmospheric concentration of CO_2, the methane and long-term ozone parameters (*e*-folding time and RF-yrs), the reference temperature change, and the aviation emissions inventories. The probability distributions applied to the aviation emissions inventories are representative of the uncertainties in current methods for estimating these inventories (FAA, 2005 a, b). Other parameters we treat by exercising different choices in the model or by exploring different scenarios, as is the case for the discount rate, the values of radiative forcing for the short-lived impacts, the efficacy values, the overall climate sensitivity, and the overall aviation and background emissions scenarios.

In Section 3.3, we specify a baseline case and then allow all of the scientific parameters to vary in a Monte Carlo analysis to show how uncertainty in these parameters produces shifts in mean and variance in different output metrics.

We conclude the presentation of results in Section 3.4 by showing how the relative contributions of CO_2 and non-CO_2 effects from aviation differ for the different metrics we have considered.

Table 3 summarizes the inputs, modeling parameters and scenarios we have used in the study. The temperature and damage responses tend to zero after about 1500 years following the last emission in the scenario. This long time scale occurs due to the slow decay of the atmospheric CO_2 perturbation. While it is not possible to confidently assess impacts over such a long time frame, it is useful to calculate the full time horizon of significant physical impacts in a manner consistent with the scenario assumptions, and then explicitly apply economic assumptions about valuing the long-term impacts. Our results show that the integrated temperature response between 800 years and 1500 years is less than 5 % of the total integrated temperature response, while the integrated damage is less than 10 % of the total integrated damage over the full 1500-year period. Given the relatively small effects of the responses after the 800-year period, we model the response for 800 years following the last emission in the scenario.

3.1 Baseline results

We first estimate the consequences of one year of aviation emissions using the IS92a background scenario and the SAGE 2003 aviation emissions and using the fixed (deterministic) baseline input values shown in Table 2. We calculate the temperature and damage of each effect independently relative to the temperature and damage of the baseline emissions scenario, assuming that each of these effects is a small perturbation to the total impact[4]. Figure 2a shows the change in temperature over time. Initially the most significant impact on surface temperature results from aviation-induced cirrus formation, although it must be noted that the level of confidence in estimating the radiative forcing due to aviation-induced cirrus is quite low (cf. SAUSEN et al., 2005). The second most significant impact on surface temperature is that due to ozone changes. On the time-scale of years, the reduced methane leads to an impact of the opposite sign. Then on a time-scale of decades to centuries the small warming due to the carbon dioxide added remains as the sole impact. The temperature change resulting from the non-CO_2 effects dominates that due to CO_2 during the years immediately following the year of emissions. The impact of CO_2 dominates in the long term.

Figure 2b illustrates the corresponding NORDHAUS and BOYER (2000) damage function. Again, the damage resulting from CO_2 dominates over the long term, despite the initially higher damage attributed to the non-CO_2 impacts during the years directly following the year of emissions.

[4]This assumption is consistent with the linear behavior of the impulse response functions; the changes in surface temperature may be added. However, for the non-linear damage function, a small difference was noted between the sum of the individual effects and the simultaneous calculation of all of the effects (a 0.01 % difference in the integrated %GDP-yr for the one-year scenario, and 0.3 % difference in the %GDP-yr for the 100-year scenario).

Table 3: Summary of modelling parameters and scenarios.

Input Variables	Source	Approach to Uncertainty	Values
Anthropogenic emissions	IS92	Scenarios	IS92a, c, e
Aviation emissions impulse fuel burn and CO_2 emissions	FAA (2005a, b)	Uniform distribution for uncertainties in fuel burn and CO_2 emissions from AEDT/SAGE	[–5 % to +5 %]
Aviation emissions impulse NO_x emissions	FAA (2005a, b)	Uniform distribution for uncertainties in NOx emissions from AEDT/SAGE	[–10 % to +10 %]
Aviation scenario	FAA (2005a, b) for current year and CAEP/4-FESG (1998) for future years	Scenarios	Fa1, Fc1, Fe1
GDP	IS92, extrapolated using a cubic spline for the period of the simulation	Scenarios	IS92a, c, e
Model Parameters			
Carbon cycle impulse response models	See Section 2	Assess results using different models	HOOSS et al. (2001) PLATTNER et al. (2001), JOOS et al. (2001)
Temperature impulse response models	See Section 2	Assess results using different models	HOOSS et al. (2001), CUBASCH et al. (1992)
Climate sensitivity	SHINE et al. (2005)	Assess results for different climate sensitivities using simple energy balance model	[1.5 K; 2.5 K; 4.5 K]
Short-lived impact radiative forcing	SAUSEN et al. (2005)	Triangular distributions about the mean; Upper and lower bounds of distributions used in sensitivity studies	See Table 1
Short-lived impact efficacy	HANSEN et al. (2005)	Set to unity or use estimates from HANSEN et al. (2005)	See Table 1
Methane lifetime	STEVENSON et al. (2004)	Assess results for different values of methane lifetime	[10.4, 11.07, 14.2] years
Reference temperature change	IPCC TAR (2001)	Triangular distribution about the mean	[0.4 K, 0.6 K, 0.8 K]
Damage function	See Section 2	Assess damage using different damage functions	ΔT, NORDHAUS and BOYER (2000) damage function
Discount rate	See Section 2	Assess net present value using different discount rates	Constant (0, 1, 3.5, 5 %), declining and randomly varying discount rates

Next we estimate the consequences of 100 years of aviation emissions using IS92a and Fa1 emissions scenarios with fixed inputs (see Table 2), as shown in Figure 3. In this case the short-lived effects make a larger contribution to the overall impact. As with the single year results, aviation induced cirrus and ozone make the largest contribution during the period in which emissions occur, although we note once more that the level of confidence in estimating the radiative forcing due to aviation-induced cirrus is quite low (cf. SAUSEN et al., 2005). The short-lived effects are responsible for a temperature change of the same order as CO_2 during the years of the scenario. In the long term, CO_2 has the largest impact. Notably, in contrast to many other scenario analyses presented in the literature, we include the full impacts of the scenario emissions (including those that go beyond the end of the scenario year). This enables us to fully account for the impacts and costs associated with the activities that occurred in the scenario.

3.2 Sensitivity and scenario analyses

In this section we individually vary some of the important model inputs and parameters, as listed in Table 3, to assess the sensitivity of the output metrics to changes in these variables. We consider the changes in surface temperature and estimated damage over time and also the integral measures of ΔT-*yr* and %GDP-yr (both integrated from 2003 to 2900). Monte Carlo analysis is used to represent the scientific uncertainty in the value of RF for a doubling of the atmospheric CO_2 concentration, the methane and long-term ozone parameters (*e*-folding time and RF-yrs), and the reference temperature change using probabilistic distributions as described in

Table 4: Sensitivity study – estimated contributions of discount rate, short-lived RFs, efficacy values and climate sensitivity to mean and standard deviation shift in key output variables. § Baseline case: Discount rate = 3.5 %, short-lived RF*s = reference value from SAUSEN et al. (2005), short-lived efficacies = all set to 1, climate sensitivity = 2.5K. † Lower and upper bounds of short-lived RF*s are based on IPCC TAR limits (See Table 1). ‡ Short-lived efficacy values from HANSEN et al., 2005 (see Table 1.) *Matched background emission scenarios are used. (IS92a-Fa1, IS92c-Fc1, IS92e-Fe1).

		Integrated Temperature Change		Integrated Damage Estimate		NPV Estimate	
Case		**Mean [K-yr]**	**Std dev. [K-yr]**	**Mean [%GDP-yr]**	**Std dev. [%GDP-yr]**	**Mean [$]**	**Std dev. [$]**
Baseline§		16	0.64	0.58	0.04	4800E9	340E9
Case		**% Mean shift‡**	**% Std dev. shift‡**	**% Mean shift‡**	**% Std dev. shift‡**	**% Mean shift‡**	**% Std dev. shift‡**
Discount rate	0 %	–	–	–	–	89100 %	105000 %
	1 %	–	–	–	–	1520 %	1750 %
	5 %	–	–	–	–	–62 %	–63 %
RF* short-lived†	lower	–39 %	–26 %	–24 %	–16%	–57 %	–46 %
	upper	71 %	65 %	47 %	38%	106 %	94 %
Short-lived efficacy	HANSEN et al., (2005)‡	–9 %	-2 %	–6 %	–4 %	–12 %	–8 %
Climate sensitivity	1.5K	–42 %	–42 %	–67 %	–66 %	-65 %	–61 %
	4.5K	84 %	84 %	239 %	233 %	200 %	185 %
Aviation Scenario*	Fc1	44 %	58 %	5 %	14 %	–74 %	–72 %
	Fe1	16 %	17 %	26 %	23 %	176 %	174 %

Section 3.1. Discount rate, short-lived RFs, efficacy values, climate sensitivity and the aviation and background emissions scenarios are represented as deterministic parameters and changed one at a time relative to the baseline case. We leave these parameters as deterministic to directly illustrate the impacts of setting them at the high and low values of the expected ranges. For the baseline case, we use the Fa1 emissions scenario and assume the mean values of the short-lived RFs as shown in Table 1, efficacy values set to unity, a climate sensitivity of 2.5 K and a discount rate of 3.5 %. For the sensitivity studies we vary the discount rate from 0 % to 5 %, we change the short-lived RFs from the lower bound to the upper bound of the triangular distribution given in Table 1, we change the efficacy values from unity to those shown in Table 1, we change the climate sensitivity from 1.5 K to 4.5 K, and use aviation scenarios Fc1 and Fe1 matched with background anthropogenic scenarios IS92c and IS92e respectively.

The results of the sensitivity analyses are summarized in Table 4. For the ranges of parameters considered, the effects on integrated temperature change due to varying the short-lived RFs and the climate sensitivity are similar. However, due to the non-linear dependence of the damage function on changes in temperature, overall climate sensitivity is relatively more important in setting the integrated damage estimate. For the net present value, effects of scientific uncertainties are much smaller than the effects produced by changes in discount rate, although changes in climate sensitivity are still significant. Changing the efficacy values produces relatively smaller effects for the ranges and output metrics we have considered.

The results obtained for the different emissions scenarios illustrate the complex relationship between aviation operations and climate impact, and, in particular, the sensitivity to background emissions levels. Relative to the baseline Fa1 case, the aviation CO_2 emissions for the low (Fc1) and high (Fe1) growth cases are changed –36 % and +47 %, respectively. However, as shown in Table 4, the changes in $\Delta T\text{-}yr$ are +44 % for the low growth scenario and +16 % for the high growth scenario. Marginal CO_2-related temperature changes are higher at lower background CO_2 concentrations due to the loga-

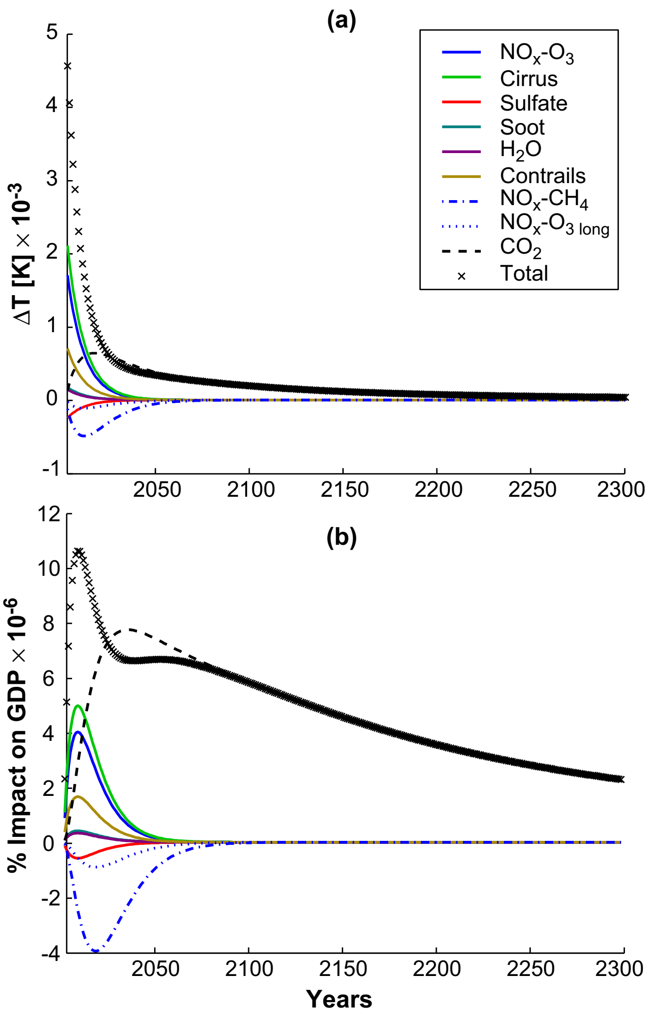

Figure 2: a) Baseline temperature change for aviation emissions impulse with fixed inputs. Impacts are calculated 800 years from the time of the last emissions. b) Baseline damage function aviation emissions impulse with fixed inputs, NORDHAUS and BOYER (2000). Impacts are calculated 800 years from the time of the last emissions. For clarity we show only the impacts to 2300.

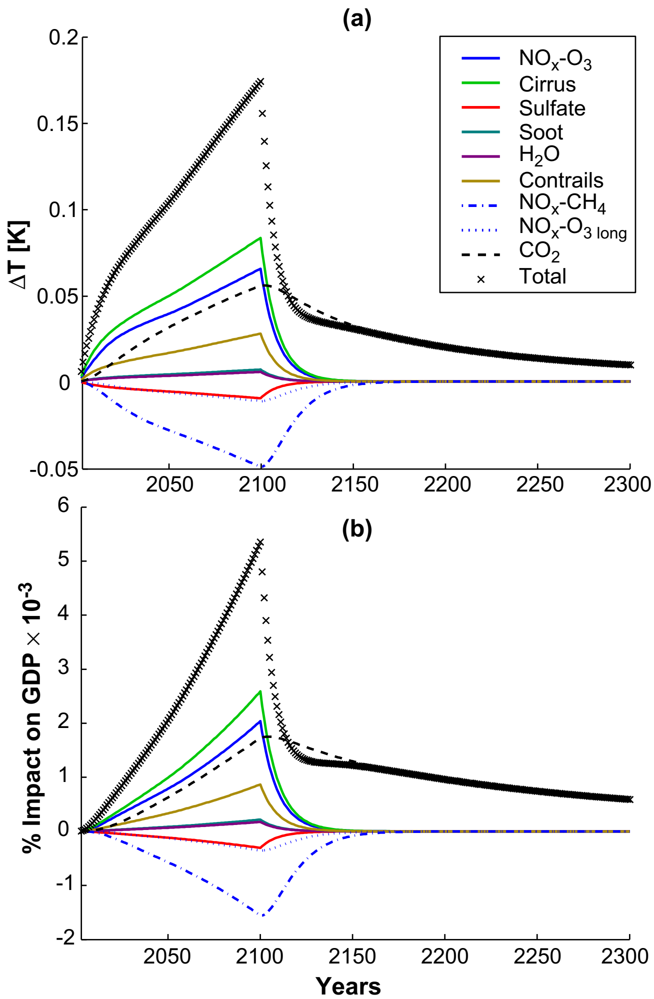

Figure 3: a) Baseline temperature change for 100 years of aviation emissions (Fa1) with fixed inputs. Impacts are calculated 800 years from the time of the last emissions. b) Baseline damage function for 100 years of aviation emissions (Fa1) with fixed inputs. NORDHAUS and BOYER, 2000. Impacts are calculated 800 years from the time of the last emissions. For clarity we show only the impacts to 2300.

rithmic relationship between CO_2 radiative forcing and concentration levels, while non-CO_2 effects are proportional to total fuel burn or NO_x emissions and are not sensitive to background levels in our model. For the low growth IS92c scenario, the total anthropogenic CO_2 emissions up to the year 2900 are 6 % of the total CO_2 emissions for the baseline IS92a scenario. For the high growth IS92e scenario, the total CO_2 emissions up to year 2900 are 211 % of those for the baseline IS92a scenario. For reference, the contributions of aviation CO_2 emissions to total anthropogenic CO_2 emissions for the first 100 years of the scenario (after which the aviation emissions are assumed to be zero) are 3.28 %, 2.45 % and 2.42 % for the low, baseline, and high growth scenarios respectively.

For the low growth IS92c-Fc1 scenario, integrated temperature change due to aviation increases relative to the baseline IS92a-Fa1 case due to the increased CO_2 effects that dominate at low background concentrations (although this increase is partly offset by decreased non-CO_2 effects relative to the baseline case). For the high growth IS92e-Fe1 scenario, non-CO_2 aviation effects become relatively more significant compared to the baseline case due to increased aviation emissions rates. These increased effects are partially offset by lower marginal effects related to CO_2, resulting in a smaller net increase in integrated temperature change. It is also important to note that when the aviation emissions in the scenario end after 100 years, the IS92c background emissions scenario reaches a stabilization limit while the IS92e scenario continues at a high growth rate. This difference in growth affects the relative temporal behavior of temperature change due to aviation CO_2 effects. Damage increases for both the low and high growth sce-

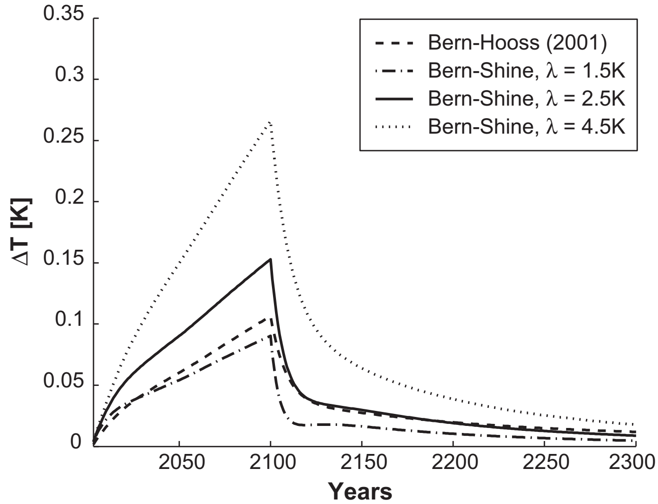

Figure 4: Impact of climate sensitivity on temperature response for aviation scenario Fa1. Note that the solid curve is the same as the total (bold x) curve in Figure 3a. Impacts are calculated 800 years from the time of the last emissions. For clarity we show only the impacts to 2300.

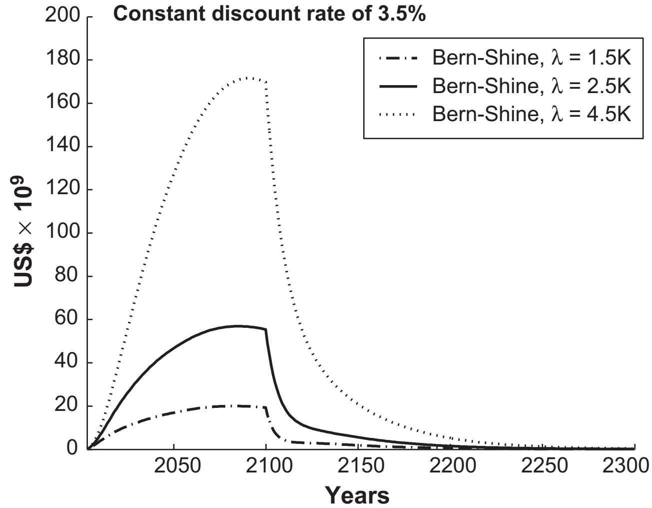

Figure 5: Impact of climate sensitivity on present valuation of climate impact. Impacts are calculated 800 years from the time of the last emissions. For clarity we show only the impacts to 2300.

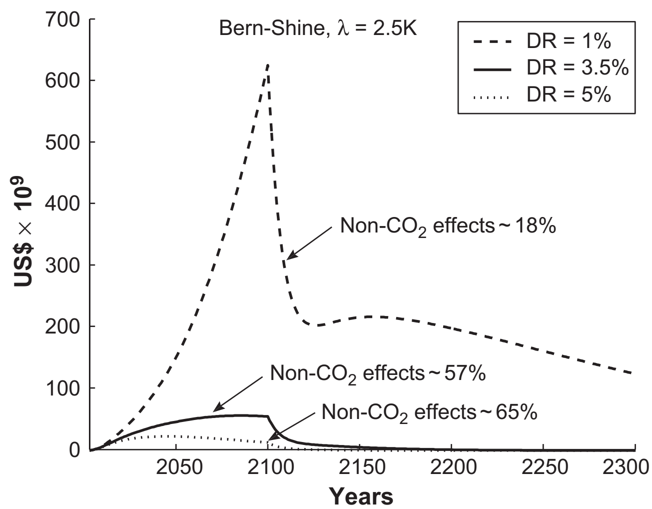

Figure 6: Impact of discount rate on present value of climate costs for aviation scenario Fa1. Damage calculated using NORDHAUS and BOYER (2000). Note that the solid curve here matches the solid curve in Figure 5.

narios, but the change is not proportional to temperature change because of the non-linear nature of the damage function. Finally, NPV trends are largely determined by the choice of discount rate. Since a large proportion of the integrated temperature change in the IS92c-Fc1 case occurs in the distant future, the impacts become negligible when discounting at 3.5 %. Most of the temperature change happens early in the IS92e-Fe1 case and therefore even with discounting, the resulting NPV is higher than the baseline IS92a-Fa1 scenario.

We now illustrate some of the results of the sensitivity and scenario analyses graphically. Figure 4 shows the impact of climate sensitivity on temperature response for aviation scenario Fa1, as described in Equation (2.5). As expected, higher climate sensitivities result in an increased temperature response. Figure 4 also compares the results obtained using the Shine et al. (2005) approach to those obtained using impulse response models derived from the higher fidelity GCM simulations of HOOSS et al. (2001), which had an effective climate sensitivity of 2.39 K. The HOOSS et al. (2001) result is bounded by the results obtained with climate sensitivities of 1.5 K and 4.5 K.

Figure 5 shows the impact of climate sensitivity on the present valuation of climate impact. Use of a higher climate sensitivity increases the temperature response of the model and therefore results in higher climate costs. At low discount rates, where the present value of long-lasting future effects like CO_2 is greater, climate sensitivity makes a significant contribution to the uncertainties associated with climate impact valuation.

Higher discount rates reduce the present value of impacts far in the future and will therefore tend to increase the relative valuation of short-lived impacts compared to long-lived impacts. The choice of discount rate therefore has a significant impact on how a given policy will be valued. Figure 6 summarizes the effect of different constant discount rates on present value of future costs for aviation scenario Fa1. The dashed curve shows the present value (where 2003 is the "present") of the climate impact for each year from 2003 to 2300, given a 1 % discount rate. The solid black curve shows the present value using a 3.5 % discount rate. Using a discount rate of 5 %, as shown in the dotted curve, reduces the present value further. Notably, increasing the discount rate increases the proportion of integrated damages due to non-CO_2 effects from 18 % to 65 %.

Table 5: Monte Carlo analysis input distributions.

Input Variable	Distribution
Fuel burn and CO_2 emissions increment	Uniform [min = -5 %, max = +5 %]
NO_x emissions increment	Uniform [min = -10 %, max = +10%]
Climate sensitivity	Uniform distribution between 1.5 K and 4.5 K
Short-lived RFs	Triangular, see Table 1
Short-lived efficacies	Uniform distribution between unity and estimates from HANSEN et al. (2005)
RF doubling of CO_2	Triangular, based on IPCC TAR limits
e-folding time, RF-yr of CH_4, RF-yr of long-term O_3, RF-yr of short-term O_3	Discrete distribution between month values of STEVENSON et al, 2004
Delta temperature 1900	Triangular [min = 0.4 K, mean = 0.6 K, max = 0.8 K]

3.3 Propagation of scientific uncertainties

We use a vary-all-but-one technique to better understand how individual uncertainties are propagated (cf. LEE et al., 2007). This technique uses a series of Monte Carlo analyses where the variability is removed from one variable at a time, while the other parameters are allowed to vary. In contrast to the sensitivity studies presented in the previous section, for these analyses we represent most of the scientific parameters as probabilistic distributions. All the input parameters except for the discount rate are represented with distributions. The discount rate is fixed at the baseline value of 3.5 %. Table 5 shows the input distributions used in the Monte Carlo analyses. This process allows us to evaluate the contribution of uncertainty in individual parameters to system-level bias while retaining the non-linear interactions among other random parameters.

The impacts on mean shift and standard deviation of temperature response, damage estimate, and NPV for aviation scenario Fa1 are shown in Table 6 for the triangular distributions listed in Table 5. Changes that are not significant relative to the statistical resolution of the Monte Carlo analyses are labeled "ns". At 90 % confidence, changes smaller than 2.5 % of the mean and standard deviation are not significant.

We draw two conclusions from these analyses. First, deterministic modeling is likely to underestimate the change in temperature and damage. Relative to a deterministic analysis with mean values, presenting uncertainty in scientific parameters as distributions about a mean value leads to higher estimates for temperature change and damage. This finding is reflected in the mean shift shown for the row in Table 6 labeled "deterministic" as compared to the row labeled "all varying". For the

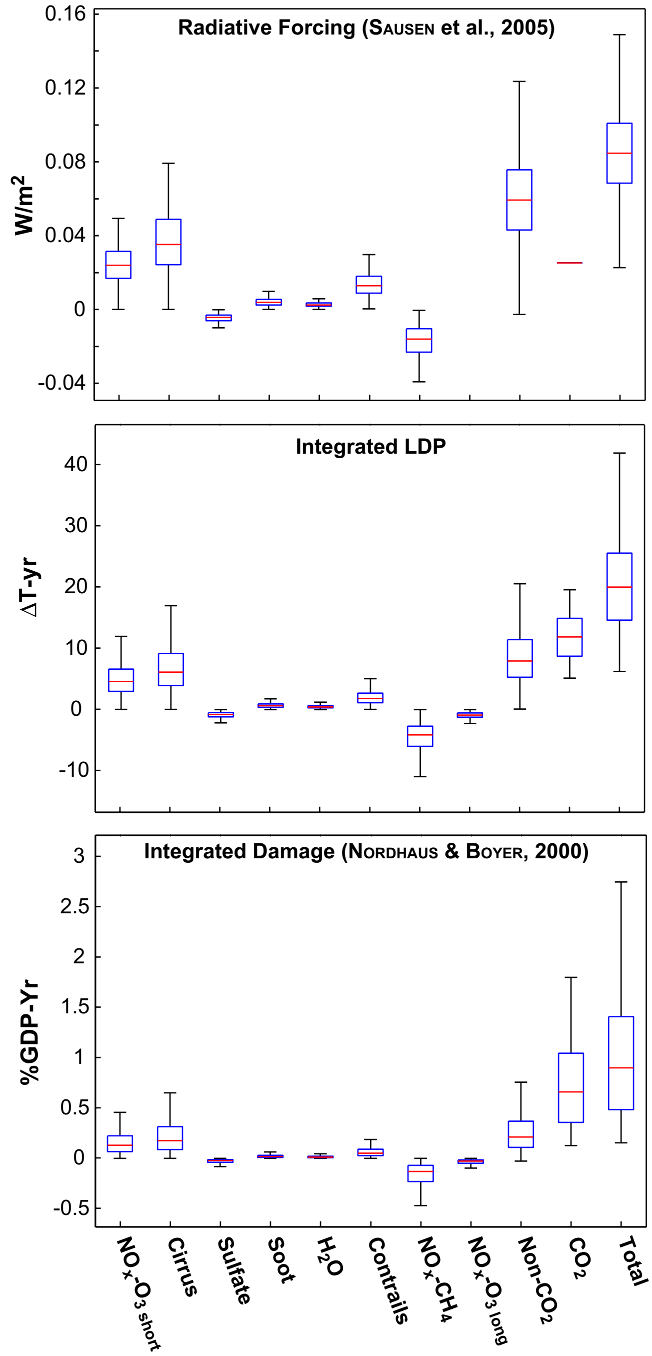

Figure 7: Comparison of metrics of climate change, radiative forcing given by SAUSEN et al. (2005) compared to the integrated ΔT-*yr* and %GDP-yr for 100 years aviation scenario given in Figures 3 based on a Monte Carlo analysis. The horizontal line in the rectangles represents the median; the upper and lower extent of the rectangles represent the upper and lower quartile of the output distribution. The error bars show the extent of the data with the upper error bound being defined as the upper quartile plus 1.5 times the interquartile range and the lower error bound is the lower quartile minus 1.5 times the interquartile range.

deterministic case, the integrated temperature change is 24 % lower, the integrated damage is 43 % lower, and the

NPV is 42 % lower. Second, the analyses show that the most significant contributors to uncertainty in the output metrics are the uncertainties in climate sensitivity and short-term RF values. This finding is demonstrated by the relative changes in the standard deviation of the output metrics when the different input parameters are each set to their deterministic mean values.

3.4 Climate metrics

The use of different metrics leads to different perceptions of the relative importance of non-CO_2 effects of aviation, as shown in Figure 7. The results shown in the figure are based on a Monte Carlo analysis where all of the input parameters shown in Table 5 are drawn randomly from their distributions. When evaluated according to radiative forcing (see, for example, IPCC (1999) and IPCC (2001)), the sum of the non-CO_2 effects of aviation is approximately three times as large as the radiative forcing due to CO_2 (SAUSEN et al., 2005). Estimates of radiative forcing for aviation represent the radiative forcing at a given time due to all prior and current aviation activity (e.g., effects of accumulated CO_2 emissions, plus present day, short-lived impacts like contrails). Since different climate effects have different time-scales, radiative forcing estimates can produce a misleading comparison of the relative importance of short-lived and long-lived effects. Further, for the purpose of comparing policies, it is necessary to have an understanding of the future impacts of a given activity, since these are the only impacts we can affect with policies.

When evaluated according to the integrated temperature impact, from the date of emissions to the cessation of significant impacts, the non-CO_2 impacts are approximately the same as those due to CO_2 . Further, when damage from the date of emissions to the cessation of significant impacts is estimated using the NORDHAUS and BOYER (2000) damage function, the impact of CO_2 is larger than that of the non-CO_2 effects.

Each metric leads to a different ranking of effects. Radiative forcing ranks the instantaneous effect of accumulated emissions up to a given point in time. The integrated temperature and damage metrics provide an indication of the importance of different effects over their full lifetime (for the time period of the emissions scenario and beyond). Discounting allows a ranking of impacts according to their present value. Different discount rates can significantly affect this ranking by emphasizing either short-term or long-term impacts as discussed in Section 3.2 and shown in Figure 7.

4 Summary and conclusions

We have presented a flexible, simplified method to assess the impact of aviation on global climate change. The method is based on impulse response models of the carbon cycle and temperature response to radiative forcing, as well as economic valuations of climate change, known as damage functions. The relative simplicity of our method and the underlying models allows us to explicitly describe the influence of uncertainties in modeling aviation emissions effects on the expected marginal future costs of aviation impacts. As scientific understanding of the different climate effects of aviation improves, updated models of climate and economics can be incorporated. We assessed the impact of aviation for one year of aviation activity, and for a 100 year aviation scenario based on FESG scenario Fa1. In each case we calculated the change in globally-averaged surface temperature, percentage impact on global gross domestic product, and the net present value of climate change. Notably, we considered the impacts of emissions over the entire period during which the effects were estimated to persist (approximately 1500 years), a period which goes well beyond the period of the emissions scenario. Thus, we captured the full time horizon for the physical impacts, against which economic assumptions about valuing the long-term impacts were explicitly applied. Such a future perspective, whether it is for a single flight or for the entire activity of a new aircraft over its lifetime increases the relative importance of the emissions effects with a longer time-scale. Two key observations can be made based on our analyses.

First, the relative importance of different effects changes depending on the metrics one considers. When evaluated according to radiative forcing, the short-lived (non-CO_2) effects of aviation appear to be approximately twice as important as those of CO_2. When evaluated according to the integrated temperature impact, the short-lived effects are approximately the same as those due to CO_2. When damage is estimated using the NORDHAUS and BOYER (2000) damage function, the impact of CO_2 is larger than that of the short-lived effects. Therefore, each metric leads to a different ranking of effects. Comparing and addressing effects solely on the basis of radiative forcing at one point in time may lead to less effective policies since the full future impacts of effects are not taken into account. Use of additional metrics, such as the marginal change in global average surface temperature and the NPV of impacts of future activities, may provide a stronger foundation for decision-making by aviation policy-makers.

Second, while there are many uncertainties about both the physical processes and economic impacts of climate change, we found the climate sensitivity, the radiative forcing of different short-lived effects, the choice of emissions scenario and the discount rate to have the most significant influence on the output metrics we considered. Other uncertainties were less important. From a policy-making point of view, it is therefore most im-

Table 6: Estimated contributions of key uncertainties to mean shift in temperature Response (Triangular distributions). § Discount rate = 3.5 %. ** Using baseline values for all inputs, see Table 2. † e-folding time, RF-yr CH_4 (or RF-yr long-term O_3), and RF-yr short-term O_3 were chosen as a group with a discrete distribution. ‡% Mean and standard deviation shifts are relative to case with all inputs varying.

	Integrated Temperature Change		Integrated Damage Estimate		NPV Estimate (fixed Discount Rate§)	
Case	**Mean [K-yr]**	**Std dev. [K-yr]**	**Mean [% GDP-yr]**	**Std dev. [% GDP-yr]**	**Mean [US$ x 10^9]**	**Std dev. [US$ x 10^9]**
All varying	21	7	0.98	0.57	8000	4700

Case	**% Mean shift‡**	**% Std dev. shift‡**	**% Mean shift‡**	**% Std dev. shift‡**	**% Mean shift‡**	**% Std dev. shift‡**
Deterministic**	–24 %	–	–43 %	–	–42 %	–
Delta temperature 1900	–	–	ns	ns	ns	ns
RF2xCO_2	ns	–3%	–4 %	–6 %	–4 %	–6 %
RF* short-lived	–10 %	–21 %	–7 %	–8 %	–15 %	–22 %
Short-lived efficacy	3 %	ns	ns	ns	4 %	ns
Emissions increment (fuelburn, CO_2)	ns	ns	ns	ns	ns	ns
Emissions increment (NO_X)	ns	ns	ns	ns	ns	ns
e-folding time & RF-yr CH_4 & RF-yr short-term O_3†	ns	–3%	ns	ns	–3 %	–4 %
e-folding time & RF-yr long-term O_3 & RF-yr short-term O_3†	ns	ns	ns	ns	ns	ns
Climate sensitivity	–18 %	–61 %	–38 %	–8 5%	–34 %	–73 %

portant to explicitly represent the uncertainty in climate sensitivity and short-lived effects (in particular contrails and aviation-induced cirrus cloudiness), and to represent different choices for discount rate and ranges of plausible emissions scenarios. More certain values for climate sensitivity and the radiative forcing values for short-lived effects may become available as our understanding of the physical processes involved in climate change improves. In contrast, determining discount rates and methods involves ethical value judgments that cannot be made easier with improved scientific or economic understanding. Likewise, our ability to accurately predict future emissions scenarios is not expected to improve dramatically over time.

Our understanding of the science and economics of climate change is such that predictions are uncertain and depend on many assumptions. Our method is not intended to provide an absolute answer or single best estimate, rather it is intended to provide a basis on which to compare policies under different assumptions and scenarios.

5 Acknowledgements

This work was supported by the Office of Environment and Energy, U.S. Federal Aviation Administration under Contract DTFAWA-05-D-00012. The effort was managed by Maryalice Locke. Mina Jun was partially supported by the Korea Science and Engineering Foundation Grant (No. D00076). We thank Professors Keith Shine, Robert Sausen and Donald Wuebbles for their very helpful critique of this work, and for the many suggestions they made for improving the work.

References

CLINE, W.R., 2004: Meeting the challenge of global warming. – In: LOMBORG, B. (Ed.): Global crises, global solutions. Cambridge University Press, Cambridge. http://assets.cambridge.org/052186/6790/excerpt/0521866790_excerpt.pdf

CUBASCH, U., K. HASSELMANN, H. HÖCK, E. MAIER-REIMER, U. MIKOLAJEWICZ, B.D. SANTER, R. SAUSEN, 1992: Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. – Climate Dynam. **8**, 55–69, DOI 10.1007/BF00209163, http://dx.doi.org/10.1007/BF00209163

CAEP/4-FESG, 1998: Report 4. Report of the Forecasting and Economic Analysis Sub-Group (FESG): Long-Range Scenarios. International Civil Aviation Organization Committee on Aviation Environmental Protection Steering Group Meeting, Canberra, Australia, January 1998, 131 pp.

ELGHALI, L., 2002: Decision Support Tools for Environmental Policy Decisions and their Relevance to Life Cycle Assessment. – Working Paper, Centre for Environmental Strategy, University of Surrey, August 2002.

FEDERAL AVIATION ADMINISTRATION, 2005a: SAGE Version 1.5 Technical Manual. – FAA-EE-2005-01, Federal Aviation Administration, Washington D.C., www.faa.gov/about/office_org/headquarters_offices/aep/models/sage/

—, 2005b: SAGE Validation Assessment, Model Assumptions and Uncertainties, FAA-EE-2005-03. – Federal Aviation Administration, Washington D.C., www.faa.gov/about/office_org/headquarters_offices/aep/models/sage/

FORSTER,P.M. DE F., K.P. SHINE, N. STUBER, 2006: It is premature to include non-CO_2 effects of aviation in emission trading schemes. – Atmos. Environ. **40**, 1117–1121, http://dx.doi.org/10.1016/j.atmosenv.2005.11.005

FUGLESTVEDT, J.S., T.K. BERNTSEN, O. GODAL, R. SAUSEN, K.P. SHINE, T. SKODVIN, 2003: Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. – Climatic Change **58**, DOI 10.1023/A:1023905326842, http://dx.doi.org/10.1023/A:1023905326842, 267–331.

GROOM, B., C. HEPBURN, P. KOUNDOURI, D. PEARCE, 2005: Declining Discount Rates: The Long and the Short of it. – Environ. Res. Econ. **32**, 445–493, DOI 10.1007/s10640-005-4681-y, http://dx.doi.org/10.1007/s10640-005-4681-y

GUO, J., C.J. HEPBURN, R.S.J. TOL, D. ANTHOFF, 2006: Discounting and the social cost of carbon: a closer look at uncertainty. – Environmental Science and Policy **9**, 205–216.

HANSEN J, M. SATO, R. RUEDY, et al., 2005: Efficacy of climate forcings. – J. Geophys. Res.-Atmos. **110**(D18), D18104.

HASSELMANN, K. R. SAUSEN, E. MAIER-REIMER, R. VOSS, 1993: On the cold start problem in transient simulations with coupled atmosphere-ocean models. – Climate Dyn. **9**, 53–61, DOI 10.1007/BF00210008, http://dx.doi.org/10.1007/BF00210008.

HASSELMANN, K., S. HASSELMANN, R. GIERING, V. OCANA, H. V. STORCH, 1997: Sensitivity Study of Optimal CO_2 Emission Paths Using a Simplified Structural Integrated Assessment Model (SIAM). – Climatic Change **37**, 345–386, DOI 10.1023/A:1005339625015, http://dx.doi.org/10.1023/A:1005339625015.

HEAL, G., 1997: Discounting and Climate Change; An Editorial Comment. – Climatic Change **37**, 335–343, DOI 10.1023/A:1005384629724, http://dx.doi.org/10.1023/A:1005384629724,

HOOSS, G., R. VOSS, K. HASSELMANN, E. MAIER-REIMER, F. JOOS, 2001: A nonlinear impulse response model of the coupled carbon cycle-climate system (NICCS). – Climate Dynam. **18**, 189–202, DOI 10.1007/s003820100170, http://dx.doi.org/10.1007/s003820100170.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), 1999: IPCC Special Report on Aviation and the Global Atmosphere, edited by J. E. PENNER et. al. – Cambridge Univ. Press, New York.

— (IPCC), 2001: Climate Change 2001: The Scientific Basis. – In: IPCC Third Assessment Report.

JACOBY, H.D., 2004: Informing climate policy given incommensurable benefits estimates. – Global Environ. Change Part A **14**, 287–297, http://www.sciencedirect.com/ science/article/B6VFV-4D3W26H-4/2/5f9fc13240478f4f0d96e701d100c8ed

JOOS, F., I.C. PRENTICE, S. SITCH, R. MEYER, G. HOOSS, G.-K. PLATTNER, S. GERBER, K. HASSELMANN, 2001: Global warming feedbacks on terrestrial carbon uptake under the IPCC emission scenarios. – Global Biogeochem. Cycles **15**, 891–907.

LEE, J.J., I.A. WAITZ, B.Y. KIM, G.G. FLEMING, L. MAURICE, C.A. HOLSCLAW, 2007: System for assessing Aviation's Global Emissions (SAGE): Uncertainty Assessment. – Transportation Research, Part D **12**, 381–395.

LIND, R.C., 1982: A primer on the major issues relating to the discount rate for evaluating national energy options. – In: Lind, R.C., K.J. Arrow, G.R. Corey, P. Dasgupta, A.K. Sen, T. Stauffer, J.E. Stiglitz, J.A. Stockfisch, R. Wilson (Eds): Discounting for time and risk in energy policy. Resources for the Future, Washington, D.C., Distributed by the Johns Hopkins University Press, Baltimore.

MENDELSOHN, R., W. MORRISON, M.E. SCHLESINGER, N.G. ANDRONOVA, 2000: Country-Specific Market Impacts of Climate Change. – Climatic Change **45**, 553–569, DOI 10.1023/A:1005598717174, http://dx.doi.org/10.1023/A:1005598717174

NORDHAUS, W.D., 1997: Discounting In Economics and Climate Change; An Editorial Comment. – Climatic Change **37**, 315–328, DOI 10.1023/A:1005347001731, http://dx.doi.org/10.1023/A:1005347001731.

NORDHAUS, W.D., J. BOYER, 2000: Warming the world: economic models of global warming. – MIT Press, Cambridge, USA.

PEARCE, D., 2003: The social cost of carbon and its policy implications. – Oxford Rev. Econ. Policy **19**, 362–384.

PEPPER, W.J., X. XING, R.S. CHEN, R.H. MOSS (Eds.), 2005: Intergovernmental Panel on Climate Change (IPCC) Scenarios 1992 (IS92), A to F, Digital Version 1.1, Palisades, NY: CIESIN, Columbia University. – http://sedac.ciesin.columbia.edu/ddc/.

PLATTNER, G.-K., F. JOOS, T.F. STOCKER, O. MARCHAL, 2001: Feedback mechanisms and sensitivities of ocean carbon uptake under global warming. – Tellus **53**B, 564–592.

POPPER, S., 2006: Letters to the Editor: The Economist, 5 August 2006, 18.

SAUSEN, R., U. SCHUMANN, 2000: Estimates of the Climate Response to Aircraft CO_2 and NO_x Emissions Scenarios. – Climatic Change **44**, 27–58, DOI 10.1023/A:1005579306109, http://dx.doi.org/10.1023/A:1005579306109

SAUSEN R., I. ISAKSEN, V. GREWE, D. HAUGLUSTAINE, D.S. LEE, G. MYHRE, M.O. KÖHLER, G. PITARI, U.

SCHUMANN, F. STORDAL, C. ZEREFOS, 2005: Aviation radiative forcing in 2000: An update on IPCC (1999). – Meteorol. Z. **14**, 555–561, DOI: 10.1127/0941-2948/2005/0049.

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

SCHNEIDER, S.H., 1997: Integrated assessment modeling of global climate change: Transparent rational tool for policy making or opaque screen hiding value-laden assumptions? – Environ. Model. Ass. **2**, 229–249, DOI 10.1023/A:1019090117643, http://dx.doi.org/10.1023/A:1019090117643

SCHNEIDER, S., K. KUNTZ-DURISETI, C. AZAR, 2000: Costing nonlinearities, surprises and irreversible events. – Pacific and Asian J. Energy **10**, 81–106.

SHINE, K.P., J.S. FUGLESTVEDT, K. HAILEMARIAM, N. STUBER,2005: Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. – Climatic Change **68**, 281–302, DOI 10.1007/s10584-005-4135-0.

STEVENSON D. S., R. M. DOHERTY, M. G. SANDERSON, W. J. COLLINS, C. E. JOHNSON, R. G. DERWENT, 2004: Radiative forcing from aircraft NO_x emissions: Mechanisms and seasonal dependence. – J. Geophys. Res. **109**, D17307, DOI:10.1029/2004JD004759

TOL, R.S.J., 2002a: Estimates of the damage costs of climate change. Part I: Benchmark estimates. – Environ. Res. Econ. **21**, 47–73.

—, 2002b: Estimates of the damage costs of climate change. Part II: Dynamic estimates. – Environ. Res. Econ. **21**, 135–159.

WIT, R.C.N, B.H. BOON, A. VAN VELZEN, 2005: Giving wings to emissions trading, including of aviation under the European emission trading system (ETS): design and impacts. – Report for the European Commission, DG Environment, No. ENV.C>2/ETU/2004/0074r.

YOHE, G., 2002: Warming the World: Economic Models of Global Warming. – J. Econ. Literature **40**, 573–574.