Metric choice for trading off short- and long-lived climate forcers

A transdisciplinary approach
using the example of aviation

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Dipl.-Ing. TU-Berlin
Odette N. Deuber
aus Los Angeles, USA

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Vorsitzender: Prof. Dr. Dieter Scherer
Gutachter: Prof. Dr. Ottmar Edenhofer
Gutachter: Prof. Dr. Robert Sausen

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The best time to plant a tree was 20 years ago.
The second best time is now.
Proverb

Faculty Planning – Building – Environment
Institute for Landscape Architecture and Environmental Planning
Economics of Climate Change
Technical University of Berlin
D – 10623 Berlin

in co–operation with

German Aerospace Center
Institute of Atmospheric Physics
Dynamics of Atmosphere
Münchner Str. 20
D – 82234 Oberpfaffenhofen – Wessling

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Nomenclature

Symbol	Explanation
	Latin symbols
C	concentration
D	economic damage
E	efficacy
I	impact function
H	time horizon
M	metric
n	damage function exponent
r	discount rate
R	ratio
T	global-mean temperature
W	weighting function
	Units
°C	degree Celsius
ft	feet
ppm	parts per million
	Abreviations
AM	absolute metric
CBA	cost-benefit approach
CC	climate change
CEA	cost-effectiveness approach
CI	climate impact
CBDR	common but differentiated responsibility
DAI	dangerous anthropogenic interference
EM	emission
EU ETS	European Emission Trading Scheme
LLCF	long-lived climate forcers
LinClim	linear climate response model LinClim
MLCF	medium-lived climate forcers
MAC	marginal abatement costs
MDC	marginal damage costs
PI	physical impact parameter
RCP	Representative Concentration Pathway
RF	global-mean radiative forcing
RFI	Radiative Forcing Index
RQ	research question
SLCF	short-lived climate forcers
WG	Working Group
TP	turning point

Abbreviations - Institutions and Groups	
AOSIS	Alliance of Small Island States
AGDG	Aviation Global Deal Group
CATE	Centre for Aviation Transport and Environment
CICERO	Centre for International Climate and Environmental Research - Oslo
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EU	European Union
GIACC	Group on International Aviation and Climate Change
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
LDC	Least Developed Countries
MMU	Manchester Metropolitan University
OPEC	Organization of Petroleum Exporting Countries
PIK	Potsdam Institute for Climate Impact Research
UNFCCC	United Nation Framework Convention on Climate Change
Metrics and equivalence factors	
CEPT	Cost-effective Temperature Potential
EGWP	Economic Global Warming Potential
EQ	Equivalence factor
FEI	Forcing Index Equivalent
GCP	Global Cost Potential
GDP	Global Damage Potential
GTP	Global Temperature Potential
GWP	Global Warming Potential
MGTP	Mean Global Temperature Potential
RF	Global mean Radiative Forcing
TEMP	Temperature Proxy Index
Further subscripts and unit extensions	
A1	A1 scenario
$B1_{acare}$	B1acare scenario
base	base case
cba	cost-benefit policy framework
cea	cost-effectiveness policy framework
cmc	contrail mitigation case
const	constant
p	pulse
ref	reference concentration pathway
s	sustain
scen	scenario emissions
t	time
tar	target
$t_0 = T_{EM}$	point in time of emission release
t_x	end point
thres	threshold

	Emissions
CO_2	carbon dioxide
CH_4	methane
NOx	nitrogen oxide
O_3	ozone
	Greek symbols
ΔT	global-mean temperature change
ϵ	proxy for SLCF
θ-function	unit step function
δ-function	Dirac Delta function
γ	damage co-efficient
λ	climate sensitivity
τ	time constant of the earth climate system

Summary

With advancing climate change there is a growing need to include short-lived climate forcers in cost-efficient mitigation strategies to achieve international climate policy targets. Simple measures, so called climate metrics are required to compare the climate impact of perturbations with distinct different atmospheric lifetimes and atmospheric properties in view of defined policy targets. A multitude of physical and economic emission metrics have been presented in the literature. However, only few scholarly papers exist which consider metrics from a meta-perspective, including atmospheric and economic sciences, and which allow a clearly structured discussion. Further, in particular, metric values for trading-off SLCF and CO_2 are highly ambiguous. Choices in climate metric design determine decisively the relative weighting of SLCF and CO_2. In aviation, there is a particular need for agreeing on a tool to weigh perturbation with distinctly different atmospheric lifetimes. Short-lived perturbations (linear contrails, contrail cirrus and nitrogen oxide induced ozone) contribute to a significant share to the sector's climate impact.

This dissertation suggests that promoting a transdisciplinary approach to climate metrics has the potential to clarify the role of climate metric choices, particularly for trading-off short- and long-lived climate forcers. The articles assembled in this cumulative dissertation aim at enhancing the understanding of the atmospheric scientific, economic and policy aspects in metric choices: for climate metric design in general, for climate metrics to evaluate short- and long-lived climate forcers and for the practical example, the relative weighting of aviation-induced contrails and CO_2.

To start, the dissertation presents a physico-economic framework on climate metric design, based on the underlying impact and weighting function of metrics. The framework allows classifying climate metrics from the literature in a straightforward manner. The analysis illustrates that from the economics perspective, the Global Damage Potential can be considered as a first-best benchmark metric since it ensures that the trade-off between different forcing agents is efficient. Virtually all climate metrics can be constructed as variants of the Global Damage Potential. The framework facilitates for the first time a structured discussion on climate metrics since it reveals normative assumptions and simplifications that are implicit to the choice of a climate metric. The evaluation of commonly used metric approaches in terms of uncertainties reveals that the choice of metric is largely coined by trade-offs between different kinds of uncertainties, explicit ones which are directly linked to operational feasibility and implicit structural ones which reflect the degree of policy relevance.

A quantitative climate metric assessment focuses on a generic trade-off situation in aviation. An evaluation framework is presented to demonstrate the impact of individual physical metric choices on the preferred mitigation strategy. The concept of a turning point is established, which indicates the point in time where the mitigation of a short-term effect (e. g. line – shaped contrails) at the expense of a counteracting long-term effect (e. g. CO_2) becomes preferable. The analysis shows that in the considered generic situation, some physical metrics are better suited than others to trade off short- and long-lived climate effects for obtaining a robust policy recommendation. The preferred mitigation strategy depends particularly on the evaluation horizon, over which climate impacts are to be minimised (cost-benefit approach) and the selected aviation emission type (pulse, sustained, scenario). At any stage, value judgements must guide the required policy decision on metric options. However, including not only linear contrails but also contrail cirrus in the assessment leads to a situation in which normative decisions become secondary. The mitigation of aviation-induced cloudiness becomes preferable.

Subsequently, the common characteristic of short-lived climate forcers (SLCF), the short atmospheric lifetime is used to present a generic approach for relating the climate effect of SLCF to that of CO_2. It is distinguished between three alternative types of metric-based factors to derive CO_2 equivalences for SLCF. Within the generalized approach, numerical values for a wide range of parameter assumptions are derived. The practical application is demonstrated using the example of aviation-induced cloudiness. The evaluation of CO_2 equivalences for SLCF tends to be more sensitive to SLCF specific physical uncertainties and the normative choice of a discount rate than to the choice of a physical or economic metric approach. The ability of physical metrics to approximate economic-based metrics depends on atmospheric concentration levels and trends. Under reference conditions, physical CO_2 equivalences for SLCF could provide an adequate proxy for economic ones. The latter, however, allow detailed insight into structural uncertainties.

A book article, finally, provides a review of the negotiation process in international aviation as background analysis. It explores the political setting for introducing binding, globally harmonised climate targets to limit the aviation-induced contribution to climate change. The policy analysis demonstrates that negotiating climate policies to limit emissions from international aviation has proven to be exceedingly difficult. The article presents possible options to include international aviation in a binding global climate regime and relates them to the negotiation positions of different actors. Special attention is paid to the global sectoral approach. The latter allows to raise revenues for adaptation to climate change in developing countries.

The dissertation reveals that when trading off SLCF and CO_2 on the basis of emission-based global- and annual-mean metrics, the basic challenges of metric design persist, some of the critical design challenges, however, reinforce due to the nature of SLCF: the relative weighting of SLCF and CO_2 is more sensitive to scientific uncertainties and normative value judgements with respect to the time frame and policy approach than to the selected metric approach (physical, physico-economic). The metrics or CO_2 equivalences for SLCF are expected to a large variability when scientific knowledge on the climate system and the small scale climate impacts of SLCF advances and the perceived urgency of near-term mitigation evolves.

Finally, in a climate regime which aims at limiting not only long-term climate change but also controlling the rate of climate change, a multi-gas strategy with a single metric for all types of climate perturbation comes to its limit. While metrics and CO_2 equivalences for SLCF treat SLCF and CO_2 as substitutes, action on limiting short- and long-lived forcers are rather complements. This could be subject to further research.

Zusammenfassung

Mit fortschreitendem Klimawandel steigt der Bedarf nicht nur lang- sondern auch kurzlebige klimarelevante Emissionen in Vermeidungsstrategien zur Erreichung klimapolitischer Ziele zu berücksichtigen. Um dies in der Praxis zu realisieren, werden einfache Maßzahlen, sogenannte Klimametriken benötigt. Sie vergleichen die Wirkung von klimawirksamen Spurenstoffen mit sehr unterschiedlichen atmosphärischen Verweilzeiten und Eigenschaften in Hinblick auf definierte Politikziele. In der Literatur werden eine Vielzahl an naturwissenschaftlichen und ökonomischen Klimametriken vorgestellt. Es gibt jedoch nur wenige Veröffentlichungen, die Metriken aus einer physikalischen und ökonomischen Meta-Perspektive betrachten, und eine klar strukturierte Diskussion ermöglichen. Hinzu kommt, dass insbesondere Metrikwerte zur Bewertung kurzlebiger Klimaantriebe eine sehr große Bandbreite aufweisen. Der Bedarf an einer Metrik zur Bewertung kurzlebiger Spurenstoffe besteht insbesondere im Luftverkehr. Kurzlebige Effekte (Kondensstreifen, Zirruswolken und stickstoffinduziertes Ozon) verursachen einen bedeutenden Anteil der Klimawirkung in diesem Sektor.

Diese Dissertation zeigt, dass ein transdisziplinärer Ansatz eine zentrale Rolle bei der Ausgestaltung von Klimametriken spielen sollte, insbesondere bei der Bewertung von kurz- und langlebigen Klimaantrieben. Das Design von Klimametriken erfordert ein gemeinsames Verständnis der wissenschaftlichen Disziplinen sowie eine enge Zusammenarbeit zwischen Wissenschaft und klimapolitischen Entscheidungsträgern. Die Aufsätze in dieser kummulativ angelegten Dissertation zielen darauf ab, das Verständnis für atmosphärenphysikalische, ökonomische und politische Aspekte im Metrikdesign zu fördern: allgemein für Metriken, für Metriken zur Bewertung sehr kurzlebiger Spurenstoffe sowie für das praktische Beispiel der relativen Gewichtung der luftverkehrsbedingten Wolkenbildung und CO_2.

Die Dissertation stellt zunächst einen physikalisch-ökonomischen Bewertungsrahmen für Klimametriken vor. Die Grundlage des Konzepts bilden die der Metrik zugrunde liegenden Wirkungs- und Gewichtungsfunktion. Der Bewertungsrahmen erlaubt es erstmalig, alle in der Literatur vorgestellten Klimametriken strukturiert zu klassifizieren. Die Analyse macht deutlich, dass aus ökono-

mischer Perspektive das Globale Schadenspotenzial als 'erst-beste' Benchmark-Metrik betrachtet werden kann. Es stellt sicher, dass die Abwägung bei der Vermeidung verschiedener Klimaantrieben kosteneffizient ausfällt. Praktisch alle Klimametriken können als Varianten des Globalen Schadenspotenzials dargestellt werden. Der Bewertungsrahmen vereinfacht eine Diskussion über Metriken, da er normative Werturteile und Vereinfachungen offenlegt, die implizit der Metriken zugrunde gelegt sind. Die Bewertung der gängigen Metriken mit Blick auf die Unsicherheiten zeigt, dass die Wahl des Metrikansatzes von einem Trade-off zwischen verschiedenen Arten an Unsicherheiten geprägt ist: explizite Unsicherheiten, die einen direkten Bezug zur Anwendbarkeit haben und implizit-strukturelle Unsicherheiten, die das Maß der Politikrelevanz widerspiegeln.

Die darauf folgende quantitative Metrikbewertung bezieht sich auf einen generischen Trade-off im Luftverkehr. Ein weiterer Bewertungsrahmen legt die Auswirkung einzelner Ausgestaltungsoptionen physikalischer Metriken auf die bevorzugte Vermeidungsstrategie dar. Das Konzept des 'Wendepunkts' wird eingeführt. Der 'Wendepunkt' beschreibt den Zeitpunkt, bei dem die Vermeidung eines Kurzzeiteffekts (z.B. linienhafte Kondensstreifen) auf Kosten eines entgegenwirkenden Langzeiteffekts (z.B. CO_2) vorzuziehen ist. Die Analyse zeigt, dass in der betrachteten generischen Situation einige physikalische Metriken besser geeignet sind als andere, um kurz- und langlebige Klimaantriebe zu gewichten. Die empfohlene Vermeidungsstrategie hängt maßgeblich vom Bewertungshorizont ab, über welchen die Klimawirkungen minimiert werden (Kosten-Nutzen Analyse) und der betrachteten Emissionsart (Puls, wiederkehrender Puls, Szenario). Zu jedem Zeitpunkt müssen normative Werturteile die Ausgestaltung der Metrik begleiten. Wenn nicht nur linienhafte Kondensstreifen, sondern auch Zirruswolken in die Analyse einbezogen werden, führt dies jedoch dazu, dass normative Entscheidungen bei der Politikempfehlung eine sekundäre Rolle spielen. Die Vermeidung der Wolkeneffekte wird vorteilhaft.

In einem weiteren Schritt wird ein generischer Ansatz zur Ableitung von CO_2 Äquivalente für kurzlebige Strahlungsantriebe entwickelt. Dieser macht sich die gemeinsame Eigenschaft von sehr kurzlebigen Strahlungsantrieben zunutze. Darauf aufbauend werden drei alternative metrik-basierten Faktoren für die praktische Anwendung vorgestellt. Auf der Basis des generischen Ansatzes werden numerischen Werte für eine grosse Bandbreite an Metrikparametern ermittelt. Die Anwendung der Faktoren in der Praxis wird am Bespiel der luftverkehrsbedingten Wolkenbildung dargelegt. Die Analyse zeigt, dass die Bewertung von CO_2 Äquivalenten für kurzlebige Klimaantriebe stärker von den spezifischen physikalischen Unsicherheiten und der normativen Wahl der Diskontrate beeinflusst wird, als von der Wahl eines physikalischen oder physikalisch-ökonomischen Metrikansatzes. Die Eignung physikalischer Metriken zur Approximierung ökonomischer Metriken hängt von CO_2 Konzentrationslevel und -trend ab. Unter den betrachteten Referenzbedingungen, können physikalische CO_2 Äquivalente jedoch in angemessenem Maße ökonomische

CO_2 Äquivalente approximieren. Letztere bieten jedoch einen detaillierten Einblick in die strukturellen Unsicherheiten.

Abschließend bietet ein Buchartikel einen Rückblick auf den Verhandlungsprozess im internationalen Luftverkehr. Er untersucht die politischen Rahmenbedingungen zur Einführung verbindlicher, global harmonisierte Klimaziele im internationalen Luftverkehr. Die Politikanalyse zeigt auf, dass sich die Verhandlungen als außergewöhnlich schwierig erweisen. Optionen zur Einbeziehung des internationalen Luftverkehrs in ein verbindliches globales Klimaregime werden vorgestellt und mit Bezug auf die verschiedenen Akteure diskutiert. Besonderes Augenmerk liegt auf dem globalen sektoralen Ansatz. Dieser ermöglicht es, Erlöse für die Anpassungsmaßnahmen an den Klimawandel in Entwicklungsländern zu generieren.

Die Dissertation zeigt, dass bei der Gewichtung von kurz- und langlebigen Klimaantrieben auf der Grundlage von global- und jährlich gemittelter Emissionsmetriken, die grundlegenden Herausforderungen im Design von Metriken bestehen bleiben. Einige Ausgestaltungsoptionen gewinnen jedoch aufgrund der unterschiedlichen Verweilzeiten der Spurenstoffe an Bedeutung: die relative Gewichtung der kurzlebigen Klimaantrieben mit CO_2 wird stark von wissenschaftlichen Unsicherheiten geprägt und normative Werturteile in Bezug auf die zeitliche Bewertung sowie auf den gewählte Politikansatz spielen eine größere Rolle. Die Metriken für kurzlebige Strahlungsantriebe werden erwartungsgemäss einer größeren Variabilität unterliegen, wenn sich die wissenschaftlichen Erkenntisse über das Klimasystem und insbesondere den kleinräumigen Klimaeffekte weiterentwickeln und sich die wahrgenommene Dringlichkeit von kurzfristiger Vermeidungsmaßnahmen bei fortschreitendem Klimawandel verstärkt.

In einem Klimaregime, das auf die Begrenzung sowohl von langfristigem Klimawandel als auch von kurzfristig relativen Änderungen des Klimasystems abzielt, stößt eine Multigas-Strategie mit einem einzelnen Metrikwert für alle Arten an klimawirksamen Spurenstoffen an ihre Grenzen. Während die Metriken und CO_2-Äquivalente die kurzlebigen Strahlungsantriebe und CO_2 als Substitute betrachten, sind Maßnahmen zur Begrenzung von kurz- und langlebigen Strahlungsantrieben dann eher als komplementär zu betrachten. Dies könnte Gegenstand zukünftiger Forschung sein.

Chapter 1

Introduction

This introduction outlines the climate policy context and specifies the objectives of this thesis. It starts with a broad perspective on climate science, policy and mitigation (Section 1.1), highlights important particularities of the aviation sector (Section 1.2) and introduces the rationale and design of climate metrics (Section 1.3). The perspective and methodological approach of this thesis is specified (Section 1.4) and the contents outlined (Section 1.5).

1.1 Climate change science, policy and mitigation

1.1.1 Anthropogenic climate change

There is a growing and well-documented body of scientific evidence regarding observed trends of global warming that can be attributed to anthropogenic emissions of greenhouse gases (GHG), their precursors and aerosols associated with human activities (IPCC, 1990, 1995, 2001, 2007a, 2013). The concentration of the most important anthropogenic emitted greenhouse gas, carbon dioxide (CO_2), grew from its pre-industrial concentration of approximately 278 parts per million (ppm) to more than 390 ppm in the year 2012. Palaeoclimatological and geological evidence indicates that the present atmospheric CO_2 concentration is higher than at any time in the last 15 million years (Tripati et al., 2009). Global mean temperature gradually increased and is about 0.85 [0.65 to 1.06] °C in 2012 above pre-industrial values (IPCC 2007a, updated in Jones et al. 2012; IPCC 2013). Even if GHG emissions were substantially reduced from present levels, global warming will continue to increase in the long-term because of the inertia of the climate system and slow removal processes.

The IPCC (IPCC (2007a), also confirmed by IPCC (2013)) estimates that – depending on the degree of climate policy intervention – GHG emissions will cause an increase in global-mean temperature in the range of 1.7 °C and 7.0 °C until 2100 (Fig. 1.1).

For the Fifth Assessment Report of the IPCC (IPCC, 2013), the scientific community has defined a set of four scenarios[1], denoted Representative Concentration Pathways (RCPs). They are identified by their approximate total RF in year 2100 relative to 1750.[2] The IPCC assumes that global surface temperature change for the end of the 21st century is likely increase by 1 °C [0.3 – 1.7 °C] (RCP2.6), 1.8 °C [1.1 – 2.6 °C] (RCP4.5), 2.2 °C [1.4 – 3.1 °C] (RCP6.0) and 3.7 °C [2.6 – 4.8 °C] (RCP8.5) relative to the reference period of 1986 – 2005. Global surface temperature change for the end of the 21st century is likely to exceed 1.5 °C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2 °C for RCP6.0 and RCP8.5, and more likely than not to exceed 2 °C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6 (Fig 1.1). Warming will continue to exhibit interannual to decadal variability and will not be regionally uniform. In temperature projections, about half the uncertainty range is due to the uncertainties in the climate system response to GHG (climate sensitivity and cloud effects), the remaining uncertainty being due to different assumptions about how the world population, socio-economic and technology trends will develop throughout the 21st century.

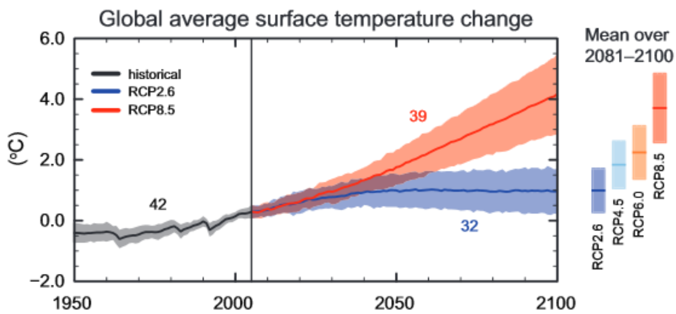

Figure 1.1: *CMIP5 multi-model simulated time series from 1950 to 2100 for a Change in global annual mean surface temperature relative to 1986 - 2005, see text and (IPCC, 2013, p. 19) for more information. Source: IPCC (2013)*

Tipping Points

Anthropogenic climate change has the potential to interfere crucially with the internal dynamics and the natural variability of the earth system. There are

[1] Three of them are intervention scenarios

[2] 2.6 W m^{-2} for RCP2.6, 4.5 W m^{-2} for RCP4.5, 6.0 W m^{-2} for RCP6.0, and 8.5 W m^{-2} for RCP8.5.

critical thresholds, so called ‘tipping points’ at which a small perturbation can adversely affect large–scale components of the earth system possibly on a long–time scale (Lenton et al., 2008; Alley et al., 2003): e. g. the loss of Arctic sea ice, the melting of ice sheets of Greenland and West Antarctica, the disturbance of the Indian summer monsoon and the large–scale Amazon rainforest and Boreal forests dieback. The threshold values of many of these climate-tipping elements lie between 1.4 °C and 4.3 °C above the current temperature level (Ramanathan and Feng, 2008). The anticipated global warming overlaps and surpasses these values and might trigger at least some of these events.

Rate of Change

Palaeoclimatological information supports the theory that the current global climate change is much more rapid and very unusual in the context of past changes (IPCC, 2007a; Marcott et al., 2013). The first 12 years of the current century (2001 – 2012) rank among the 14 warmest in the 133–year period of record (NASA, 2013). In the 1990–ies the average global-mean temperature increased more rapidly than ever before (0.24 °C). However, global–mean temperatures in the last decade were not rising as fast as predicted (e. g. Otto et al., 2013). However, the short period of observed temperature flattening is hardly a significant time scale in order to predict a change in trend. The earth system continues to warm, several studies (e. g. Meehl et al., 2011; Balmaseda et al., 2013) suggest that observed ‘warming hiatus’ occurs due to the inertia of ocean heat uptake, the warming took places particularly in the deeper layers of the oceans. Even though climate scientist have to adjust their near-term projections due to the temperature flats, the medium to long-term challenge of anthropogenic climate change remains invariant.

Regional scale impacts and damages

The projected global-mean temperature increases will very likely lead to, and go along with, numerous regional scale changes (IPCC, 2007a), continuing observed recent trends. Among such changes are the reduction of snow–covered areas, the shrinking of sea ice, the increased frequency of hot extremes, heat waves and heavy precipitation, the increase in tropical cyclone intensity, general precipitation increases in high latitudes and, respectively, decreases in most subtropical land regions. The projected global–mean temperature increase results in adverse ‘market impacts’ which directly affect the economy such as impacts on agricultural production, critical infrastructures (e. g. electricity and transport infrastructure) and on coastal safety (e. g. World Bank, 2013). Additionally, ‘non-market impacts’ will occur which affect humans and society more broadly: the loss of biodiversity and water availability, infectious diseases, social conflicts, migration and similar socio-economic impacts (Jamet and Corfee-Morlot, 2009; IPCC, 2007c). The induced economic damage and welfare loss depend decisively on the vulnerability and on the adaptive capacity of societies. Stern (2007)

e. g., estimates that without action, the overall costs of climate change will be equivalent to losing at least 5 % of global gross domestic product each year, now and for all times. Including a wider range of risks and impacts could increase this to more than 20 % of the global gross domestic.

Economic perspective and ethical dimension

The cause and effects of anthropogenic climate change are externalities, at the most basic level. All those who emit GHG trigger climate change, thereby imposing costs on society and on future generations. The emitters, however, do not face the full consequences or costs of their action neither via markets nor in other ways. In contrast to other environmental pollution where the annual flow matters, such as noise and local exhaust emissions, GHG are stock pollutants. As the atmosphere has little absorptive capacity for them they accumulate in the atmosphere; current GHG emissions only takes full effect in decades.

These aspects lead to the ethical dimensions of climate change and the factors causing it. Firstly, emissions and the projected impacts and damages are unevenly distributed across countries. As a general rule, industrialized countries are responsible for a large share of GHG emissions in the past while developing countries are expected to cope with greater impacts, higher vulnerability and smaller adaptive capacity (e. g. World Resource Institute, 2012; Watson et al., 1997; IPCC, 2007c; Edenhofer et al., 2010b; OECD, 2009; World Bank, 2013). Secondly, due to slow removal processes of GHG from the atmosphere and the inertia of the climate system, some socio-economic impacts of climate change will take effect in the distant future: future generations will have to cope with climate change damage irreversibly initiated at present.

The welfare economic perspective suggests to internalize environmental externalities. In an economically efficient mitigation response, the marginal costs of mitigation would be balanced against the marginal benefit of the emission reduction. Optimal in line with this cost-benefit policy framing would be to put a prize on each GHG e. g., by introducing market-based instruments such as taxes (Pigou, 1932) or property rights (Coase, 1960), transferable in the form of emission trading (e. g. Dales, 1968) and to let each polluter pay for the induced marginal climate damage. The marginal benefits are the avoided damages from an additional tonne of CO_2 being abated in a given emissions pathway, the social cost of GHG emissions. Addressing the delayed effect of stock pollutants, global warming policies are best analysed in an inter-temporal optimization, or so-called control framework, in which the abatement and damage costs over several time periods are traded-off to minimize the net present value of climate change costs (Nordhaus, 1991; Cline, 1992; Fankhauser et al., 1997).

Damage cost estimates, however, depend on the amount of emissions discharged in the future. The existing ones span several orders of magnitude (e. g. Tol, 1999). The range reflects beyond purely scientific uncertainties (e. g. on climate sensitivity) methodological difficulties in quantifying and monetizing climate change damages. Robust methodologies for valuing non-market impacts (e. g. valuing life loss) or for explicitly factoring in extreme, largely irreversible events are controversial, likely to understate the effects of climate change or even lacking completely (e. g. IPCC, 1995; Fankhauser et al., 1997; Weitzman, 2011; Hanemann, 2010; Perrings, 2003). Aggregating regional into global damage estimates and valuing damage distant in time e. g. in the form of a discount rate, involve value-based choices. These are crucial factors of influence on the net present value of damage cost estimate, directly linked to risk management and the ethical dimension of equity (e. g. Stern, 2007; Weitzman, 2007; Hayward, 2012).

In face of methodological difficulties to specify the damages of climate change and in face of irreversible tipping points of the climate system, the 'cost-effective policy approach' offers a pragmatic way–out. This risk management approach (also: 'second best approach' (e. g. Baumol and Oates, 1988; Tietenberg, 1992) or 'carbon budget approach' (Fankhauser, 1995)) avoids explicit damage consideration, the benefit-side of the analysis is not based on economic assessment. Instead, an upper limit for the atmospheric greenhouse gas concentration or for the warming is exogenously imposed based on ethical, political and precautionary considerations. The discounted costs of meeting the climate constraints are then minimized (Markandya et al., 2001).

Even though often abstracting from dynamics and risks, and not sufficiently accounting for ethical perspectives on justice, human rights and equity, the economic perspective on externalities and their internalization serves as an essential basis for efficient climate mitigation.

1.1.2 Inter- and transdisciplinary challenge

For addressing the complexity of anthropogenic climate change, an *transdisciplinary* problem–solving process in line with Hadorn et al. (2008) offers a reasonable way forward: The scientific disciplines work together assesses the cause of global warming and its future development, the policy–makers agree on targets based on value judgements and stakeholders and decision–makers mitigate and adapt to global warming by transforming the economies and societies, see also (Edenhofer and Kowarsch, 2012)

A transdisciplinary approach originates from the focus on a real world problem. In contrast to *multidisciplinarity*[3] and *interdisciplinarity*[4], *transdisciplinarity* has been described as a research strategy that crosses many disciplinary boundaries to create a holistic approach (e. g. Russell et al., 2008). It calls for the promotion of a common understanding and co-operation among different scientific disciplines and policy stakeholders.

A dialogue between scientists that is extended to policy– and decision–makers has to cope with a diversity of terminologies, thought processes, political perspectives and interpretations. When crossing professional cultural boundaries

[3] Disciplinary specialists work together while maintaining their disciplinary approaches and perspectives.

[4] Areas of overlap or intersection between disciplines are investigated by scientists from two or more areas.

trust is vital and this can be supported through transparency (Harris and Lyon, 2013). Communication tools that increase transparency without leading to additional complexity are best suited to integrate disciplinary methodologies, to overcome communication challenges and conflicting interests. They have the potential to facilitate the problem–solving process that is urgently needed.

The idea of transdisciplinarity is reflected in the institutional setting of the international climate policy arena. The Intergovernmental Panel on Climate Change (IPCC) was established to provide comprehensive scientific assessments on global climate change and an overview on potential adaptation and mitigation strategies. The IPCC consists of three major Working Groups (WG), concerned with the following fields of knowledge: the physical science basis (WG I), the impacts, adaptation and vulnerability (WG II) and mitigation of climate change (WG III). The current knowledge is thus integrated across the scientific disciplines. By providing scientifically well-founded knowledge, the IPCC assists governments in pronouncing value–judgements and defining norms, and decision–makers in the public and private sectors, in formulating and implementing comprehensive and cost-effective adaptation and mitigation strategies.

1.1.3 Climate policy target

The stated goal of international climate policy is to 'prevent dangerous anthropogenic interference with the climate system' (United Framework Convention on Climate Change [UNFCCC], 1992, article 2). The climate policy should be guided by considerations of the precautionary principle, intra- and intergenerational equity, the principle of 'common but differentiated responsibilities and capabilities' and a sense of 'carbon justice' to protect the most vulnerable. Mitigation strategies should be based on different socio-economic perspectives and be comprehensive and cost-effective (UNFCCC, 1992, article 3). The international community succeeded in taking critical but pivotal target decisions on acceptable outcomes and risks: It set the target of limiting the global mean surface temperature increase to a maximum of 2 °C above pre–industrialized values (Council of the European Union (2005), Copenhagen Accord 2009 and Cancun Agreement 2010). Further the international community leaves open the option of 'strengthening the long-term global goal on the basis of best available scientific knowledge' including in relation to a global–average temperature rise of 1.5 °C (Cancun Agreement and Durban Outcome).

To reach the target, however, climate policy has to overcome inherent conflict potentials between straightforward and efficient action and fundamental UNFCCC principles, and between the diversity of political perspectives and the practicability of the mitigation strategies in the real world. A major policy task is to define and implement an effective risk management strategy.

Progress in the implementation of concrete emission reduction policies has been slow. Despite positive developments in some countries, global emissions have continued to rise (Peters et al., 2012; IEA, 2013). For the year 2012 an 1.4 %

increase in global energy-related CO_2 emissions is reported (31.6 Gt IEA, 2013), a historic high, within a 'path which is more likely to result in a temperature increase of between 3.6 °C and 5.3 °C' (IEA, 2013).

The scientific community has published a number of scenario studies that assessed the implication of the 2 °C target for emission and concentration levels: e. g. 'tolerable windows' for action, scopes for action compatible with predefined climate and socio-economic constraints (Petschel-Held et al., 1999; Meinshausen et al., 2009; Stocker, 2013). Climate change cost estimates (e. g. Stern, 2007; UNEP, 2011) have been presented.

Scientific analysis (e. g. Rogelj et al., 2012, 2013; Hatfield-Dodds, 2013; Peters et al., 2012; Luderer et al., 2013; Edenhofer et al., 2010a) attests a very urgent need to act. A 2 °C pathway requires immediate significant and sustained global mitigation with the timing of measures for structural changes towards a low carbon society has a strong impact on the physical outcome and the cost of climate change. Delaying mitigation has the largest effect on cost-risk distribution and thus on the probability of limiting temperature increases to 2 °C. For example Rogelj et al. (2012) state that, indeed, the option of meeting a 2 °C target is kept even in the case that global GHG cannot be reduced before 2020. The options of meeting the target, however, would be associated with very high costs and risks and will depend on the prospects of key energy technologies. Lowering emission levels earlier would allow the political target to be achieved under a wide range of assumptions, and thus help to hedge against the risks of long-term uncertainties.

Short-lived climate forcers

In the past, international climate policy has focused primarily on limiting long-lived GHG. Long-term climate mitigation efforts, however, may not be sufficient to avoid 'dangerous anthropogenic interference in a time frame sufficient to allow ecosystems to adapt naturally to climate change'. Optimising a mitigation strategy in line with UNFCCC principles implicitly suggests complementing the long-term strategy by mitigating short- and medium-lived climate forcers (SLCF; MLCF) in a comprehensive mitigation policy (Jackson, 2009; Nature's editorial, 2009; Penner et al., 2010; UNEP, 2011; Borken-Kleefeld et al., 2011; Smith and Mizrahi, 2013) to limit the rate of change on a decadal time scale. SLCF and MLCF such as methane, black carbon, tropospheric ozone, a subset of hydrofluorocarbons and anthropogenic induced cloudiness are characterised through a relatively short lifespan in the atmosphere (hours to years, decades, but not centuries) and have a significant impact on the rate of climate change and near-term climate change (Hansen et al., 2007; Quinn et al., 2008). They account for more than half of the positive RF generated in the next 20 years (Jackson, 2009). There is, however, no need to focus first and foremost on SLCF and MLCF, a comprehensive climate policy addressing both, reductions in short- and long-lived greenhouse gas emissions obtains similar climate benefits (Smith and Mizrahi, 2013).

Including these forcers in the climate mitigation strategies enlarges the portfolio of abatement options and to have the potential to substantially enhance cost-effectiveness if there is a sizeable emission reduction volume for them compared to the large emission reduction volume of CO_2, the abatement costs are comparable to the cost of reducing CO_2 and measures and investments with the lowest specific cost are carried out first.

Mitigation of SLCF and MLCF complements strategies for adapting to the effects of climate change by delaying warming for several decades, reducing adaptation costs and mitigating risks to ecosystems and the socio-economic system.

1.2 Aviation and climate change

1.2.1 Climate impacts

As the only anthropogenic source of emission, aviation emits gases and particles directly into the upper troposphere and lower stratosphere altering the atmospheric composition without the necessity of effective upward transport (IPCC, 1999; Sausen et al., 2005; Lee et al., 2009). In the face of the unique location of its emissions, some of the aviation-induced climate impacts are direct, long-lived and common to many other anthropogenic fuel-based activities (e. g. CO_2), others are specific to aviation, indirect and (very) short-lived e. g. emissions of nitrogen oxides at cruise altitude (NOx) are particularly effective in changing the distributions and concentrations of ozone (O_3) and methane (CH_4). Aviation-induced water vapour triggers the formation of additional clouds, contrails and contrail cirrus and changes in the distribution and properties of otherwise natural clouds (Sausen, 2010).

Short-lived non-CO_2 effects

The aviation-induced short-lived effects persist only for hours (contrail, contrail cirrus), days or weeks (NOx-induced ozone, respectively) in the atmosphere. They do not accumulate in the atmosphere in the longer term (flow pollutants) and have particularly discernible impacts on local and regional climate change e. g. changes in rainfall or regional circulation patterns. The climate response of non-CO_2 effects is very sensitive to the geographical and vertical location of the triggering emission component i. e. it is influenced by a number of external physical and chemical factors, such as temperature and chemical composition of the actual background atmosphere and the altitude of the sun(e. g. Frömming et al., 2011; Stuber et al., 2006; Berntsen et al., 2006; Derwent et al., 2008; Schumann and Graf, 2013). It varies largely with cruise altitude of the aircraft (Frömming et al., 2011; Grewe et al., 2002). Modelling and predicting the climate

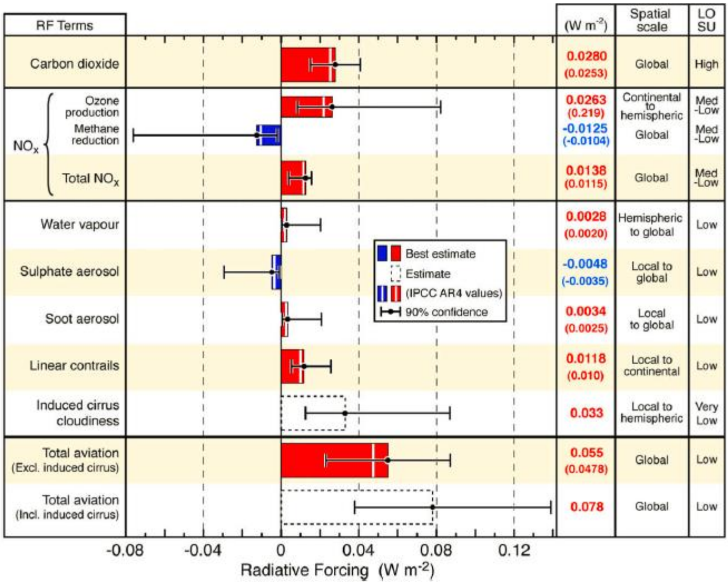

Figure 1.2: *Aviation radiative forcing component as evaluated from pre-industrial times until 2005, more details see Source. Source: Lee et al. 2009, p. 3526*

response of non-CO_2 effects is scientifically considerably less understood than that of CO_2 (Figure 1.2) due to the highly complex interaction between aerosols and clouds (contrails) and the feedback on other chemical components in the atmosphere (ozone and methane formation). Lack of empirical knowledge on consequences from an high rate of climate change makes difficult their evaluation.

Contrail and contrail cirrus

In this dissertation, contrails are considered as an important example of SLCF. Contrails are line-shaped ice clouds that form behind an aircraft according to thermodynamic theory (so-called Schmidt Appleman Criterion). They form when hot and moist exhaust gases mix with cold and sufficiently humid ambient air and saturation with respect to liquid water is reached in the process (Schmidt, 1941; Appleman, 1953; Schumann, 1996, 2005; Sausen et al., 1998). In ice-supersaturated regions contrails may persist for hours and transform into contrail cirrus (Minnis et al., 1998; Burkhardt and Kärcher, 2011; Minnis et al., 2004).

Contrails scatter incoming sunlight and reflect a part of it back to space, thus reducing the amount of solar radiation absorbed by the Earth (cooling albedo effect). In parallel, they also reduce the outgoing long-wave terrestrial radiation (warming greenhouse effect). While the net global mean radiative balance of contrails and contrail cirrus is positive (in 2005 contrails: 11.8 $mW\,m^{-2}$ (5.4 – 25.6 $mW\,m^{-2}$) , contrail cirrus: 33 $mW\,m^{-2}$ (11 – 87), Lee et al. 2009), the net radiation balance in a specific situation (cooling or warming) is determined by the incoming solar radiation, the optical properties of the contrail or contrail cirrus such as colour, particle size, optical depth, temperature and also by properties of the underlying surface (ocean, ice, landmass) (Meerkötter et al., 1999; Frömming et al., 2011; Schumann et al., 2012).

Aviation's total climate impact

In present literature, the contribution of contrail cirrus, though the largest of all aviation perturbation estimates, was considered as particular with respect to its associated uncertainty. The estimate of total aviation forcing is often expressed by either including or excluding it: The *RF* from global aviation as evaluated from pre-industrial times until 2005 is estimated to be 55 $mW\,m^{-2}$ excluding contrail cirrus (78 $mW\,m^{-2}$ including contrail cirrus), which represents some 3.5 % of current anthropogenic forcing with a large uncertainty range of 1.3 % – 10 % (4.9 % with a range of 2 % – 14 %) (Lee et al., 2009). Non-CO_2 effects account for a share of 49 % (excluding contrail cirrus) and 64 % (including contrail cirrus), respectively.

The total RF from past aviation was estimated to be higher by a factor 2 than the contribution from carbon CO_2 from this sector, even without considering the potential impact of cirrus cloud enhancement (Lee et al., 2010). The factor of total RF from aviation to that of CO_2 from aviation is referred to as Radiative Forcing Index (*RFI*). This *RFI* has been misunderstood by many policy-makers (e. g. Forster et al., 2006; Azar and Johansson, 2011). It has been used used and interpreted as the CO_2equivalent from aviation. This usage, however, is erroneous since the *RFI* gives the RF ratio in a particular year caused by all historic emissions from aviation up until that year (Forster et al., 2006; Fuglestvedt et al., 2010). *RFI* is a backward looking metric, taking into account the past and present day emissions, whereas calculating the CO_2 equivalent emissions from aviation requires a *emission-based forward looking metric*, taking into account the current and future impact on the climate, see Section 1.3.

Future projections

Although the current contribution from aviation to climate change is still very limited, its share is expected to increase by a factor of 3 to 4 over 2000 levels in 2050 (Lee et al., 2009). Emerging markets will most likely contribute considerably to these growth rates (e. g. Bows et al., 2009; Airbus, 2012). In parallel, emissions from international aviation are excluded from the binding emission targets of the Kyoto Protocol. Due to the transboundary nature and the participation of a variety of international players, limiting aviation's contribution to climate change is a 'wicked international climate change problem' (Bardwell (1991), see Chapter 5).

On a multi-decadal time scale, it is foreseeable that aviation-induced climate impacts increasingly counteract global reduction efforts of other sectors that move away from fossil fuels towards renewable energy sources, i.e. aviation's emission cannot be brought in line with the 2 °C target threshold without other sectors making significantly deeper cuts (Bows et al. 2009, Figure 1.3).

1.2.2 Climate change mitigation

Climate change mitigation measures in aviation have so far focused on CO_2, mainly driven by fuel costs. Non– CO_2effects, though relevant in terms of impact, remain unregulated (e. g. van Renssen, 2012; Wit et al., 2005a). Some CO_2 mitigation might result in potentially important trade-offs with non– CO_2 effects: For example, when enhancing propulsion efficiency of aircraft engines, contrails form at progressively lower altitudes under the same atmospheric conditions (Schumann, 2000; Schumann et al., 2000). In return, some CO_2 mitigation strategies have synergistic effects with NOx emission reduction; however, only volume measures that aim at reducing the number of flights might have likewise a positive effect on contrail formation.

There is a large potential for reducing contrail formation directly, as flying through ice-saturated regions which are favourable for contrail formation is avoidable. A straightforward concept in this respect, realisable in the short term,

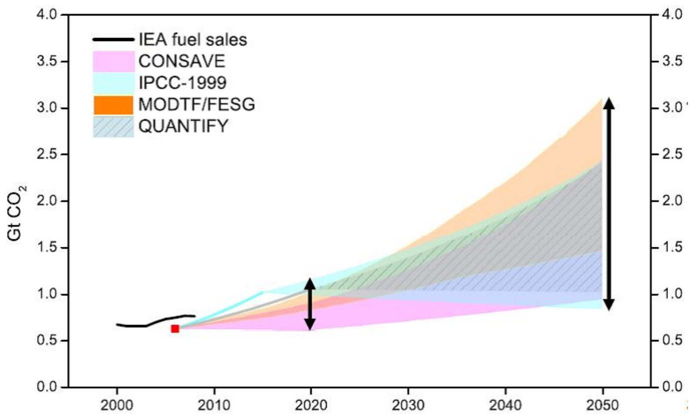

Figure 1.3: *a) Emission of CO_2 from aviation, and projection through 2050. Data from 2000 to 2009 based on IEA fuel sales data. Projections from: (MODTF/FESG, 2009); QUANTIFY project (based on (Owen et al., 2010)); (IPCC, 1999); CONSAVE project (Berghof et al., 2005). See more information in Source. Source: (UNEP, 2011)*

is to lower the cruise altitude. This would reduce, at the same time, the NOx–induced climate response (Fichter et al., 2005; Frömming et al., 2011; Grewe et al., 2002; Stordal et al., 2006; Gierens et al., 2008; Gauss et al., 2006, see Chapter 3). In some situations, only minor tactical changes of altitude are to be undertaken to avoid ice-supersaturated regions on the basis of flight-by-flight prediction of contrail formation (Mannstein et al., 2005). However, with the current aircraft designs, these operational non-CO_2 mitigation options entail a fuel burn penalty and incremental CO_2 emission. In a world of high fuel prices and policy priorities on long-term climate change mitigation, manufacturers and operators are not likely to adopt contrail mitigation options without some form of regulatory incentive or coercion.

Comprehensive and cost-effective climate policy suggests that any mitigation option (e. g. operational measures, design of aircraft and engine technology), should be assessed in view of its total climate effect. A prerequisite for such a valuation would be a robust scientific framework for quantifying and comparing the climate response of aviation-induced greenhouse effects (Green, 2005). Such a framework, however, is complex and not straightforward, due to strongly differing climate impacts of short- and long-lived climate forcers (Wit et al., 2005a; Forster et al., 2006; Lee et al., 2010). There is a need to evaluate and compare direct and indirect, local, regional and global climate effects, which have the potential to be highly non-linear. According to the Director General for Research of the European Commission "the difficulties of the problem in terms of life time and spatial release of GHG and aerosols, and the quantification of their direct and indirect effects required a sophisticated multidisciplinary research approach" (Brüning, 2010).

1.3 Climate metric design

A climate metric (short: metric) is a flexible, rapidly-available tool that enables the design of effective multi-gas climate policy instruments by converting simple and fundamental UNFCCC principles into operational mitigation approaches. Metrics are simple measures for quantitatively comparing the potential impact of different climate change mechanisms e. g. emission of GHG with different atmospheric lifetime. To be applicable they must not oversimplify the complexity of the problem and they have to retain the possibility of uncertainty assessment. Metrics facilitate assessing the relative contributions of a sector to climate change (e. g. aviation's contribution to climate change), comparing climate effects from competing technologies (e. g. climate optimised aircraft design and technologies), evaluating different types of perturbations in a given sector (e. g. non-CO_2effects versus CO_2) and evaluating the trade-off situation between different types of climate impacts (e. g. flight route optimisation).

The design of a metric is of transdisciplinary nature. It involves quantifying atmospheric and socio-economic climate impacts along the chain of impact and over large time horizons. It requires evaluating the complexity of climate impacts in line with normative policy objectives, the simple and fundamental UNFCCC principles and climate targets. The outcome should be expressed in a simple, generalised manner to facilitate an operational feasible mitigation strategy that is comprehensive, fair and efficient. In the past, climate metric design on IPCC level has been mainly treated as a physical science issue (IPCC, WG I). The need for a more interdisciplinary approach has been realised, particularly in economic science literature (Bradford, 2001; O'Neill, 2000, 2003; Godal, 2003), but also by natural scientists (e. g. Shine 2009, WG I and III, respectively). As a consequence, IPCC Expert Meetings on the Science of Metrics were held in the year 2009 (Plattner et al., 2009) and in 2012 (UNFCCC and SBSTA, 2012).

No single metric can accurately represent the climate responses of all relevant perturbations over all relevant time scales. Therefore, an appropriate, specific metric design will depend on which aspect of climate change is considered to be most important to a particular application. It needs a clear definition of the overall policy objective and an explicit set of policy decisions in line with the specific mitigation strategy (e. g. cost-effective versus cost-benefit policy framing) (Plattner et al., 2009; Fuglestvedt et al., 2003, 2010).

Emission-based metrics

An emission-based metric describes the marginal climate impact of a unit non–CO_2 emission, usually normalised to that of one unit pulse CO_2 emission (Forster et al., 2007; Fuglestvedt et al., 2010). A comprehensive derivation of emission-based climate metrics in terms of economic theory is provided in Chapter 2. Metrics serve as a multiplier for non-CO_2emissions (or more general: non–CO_2 effects) to obtain CO_2 equivalences (CO_2e), describing the amount of CO_2 emissions that would cause an equivalent climate impact as a given non–CO_2 emission.

While there is a multitude of physical and physico-economic metrics proposed in the scientific literature (see Chapter 3), some have gained specific relevance because they are either scientifically superior or simply because they have been most frequently used. Most prominent in this respect is the Global Warming Potential (GWP) commonly adopted for trading-off long-lived GHG (e. g. IPCC, 2001; Forster et al., 2007). This emission-based metric is the foundation for the principle of comprehensiveness and efficiency adopted in the UNFCCC and is thus an important tool in the implementation of the Kyoto Protocol (Article 5.3, Kyoto Protocol 1997). It compares the integrated forcing of a pulse emission of a radiative active species for a specific time horizon (Chapter 2-4).

Using the GWP as a metric has several advantages: the GWP is relatively simple to derive. The simplicity of the methodology allows other scientists to easily verify calculations and policy-makers to easily compare different forcing agents. Particular challenges arise, however, when indirect and heterogeneously-distributed SLCF with substantially different atmospheric properties are to be included in the evaluation (e. g. Forster et al. 2006, more details in Chapter 3 and 4). The limitations of this simple, purely physical metric concept have been thoroughly analysed and often criticised (Chapter 3 and (e. g. Fuglestvedt et al., 2003, 2010; Forster et al., 2007; De Cara et al., 2008)). The principal points of criticisms are that the GWP ignores the vulnerability of ecosystems and the effects on the socio-economic systems in terms of damage and welfare loss, and that the metric is not designed to guide emissions towards any stabilization target (cost-effectiveness policy framework). However, no alternative metric concept has been convincing enough so far to gain comparable policy relevance.

1.4 Objectives, research questions and methodological approach

Coming from the climate policy design challenges, the overall aim of this thesis is to explore metric choices for trading off short- and long-lived climate effects, using the example of aviation. Starting points of the analysis are the research hypothesis that climate metric design requires interdisciplinary understanding and transdisciplinary co-operation between climate policy stakeholders. With advancing climate change and an increasing rate of climate change, there is a growing need to include short-lived climate perturbation in cost-effective mitigation strategies. This requires a simple exchange rate to trade-off the climate effects from SLCF to CO_2. Choices in climate metric design decisively determine the relative weighting of the respective climate effects. In the aviation sector, there is a particular need for agreeing on a tool to weigh impacts that have a long-term effect on climate for centuries (CO_2) against very short-lived indirect effects (e. g., contrail and contrail cirrus effects).

This thesis goes beyond previous studies that have discussed individual aspects,

- by analysing the key factors for climate metric design in an interdisciplinary framework with transdisciplinary elements,
- by providing a conceptual framework for climate metrics which reveals implicit underlying assumptions and value judgements and
- by quantifying the effect of underlying metric choices on the evaluation of very short- and long-lived climate effects by using case examples.

This thesis encompasses aspects of atmospheric, economic and political science, thus operating at the interface between the research areas covered by IPCC WG I and WG III in the field of climate metrics. Beyond the purely scientific community, it addresses as target audience applied scientists and other climate policy stakeholders at the interface of science, policy and industry. It provides answers the following research questions (RQ):

RQ I How do the perspectives of different scientific disciplines and of the diverse climate policy stakeholders interact in climate metric design? How can the multitude of emission-metrics presented in literature be classified and evaluated? What are the underlying assumption, and explicit or implicit normative value judgements of the variety of alternative metrics proposed in the scientific literature? What are the rationale, the benefits and the limitations of economic considerations in climate metric design?

RQ II How do metric choices and policy decisions in metric design affect the relative importance of short- and long-lived climate forcing such as contrail and CO_2? What is the implication of a short atmospheric lifetime for the calculation of climate metrics?

RQ III How can short-lived climate forcers in aviation such as contrails be traded-off against long-lived CO_2 forcing? Which lessons can be learnt for the aviation sector?

The thesis starts with a climate metric design analysis from a meta-perspective (Chapter 2), followed by quantitative assessments (Chapters 3 and 4): Chapter 3 develops a physical metric-based evaluation framework addressing a trade-off case example (contrails and CO_2). Chapter 4 adds a generic perspective on the implication of the short atmospheric lifetime for CO_2 equivalences. A more general qualitative policy analysis with respect to aviation climate policies serves as background analysis (Chapter 5) and completes the set of publications.

A simplified modelling framework is applied, the linear response (impulse response) model LinClim. This model was developed to evaluate aviation-induced climate effects (Lim and Lee, 2006). It calculates the time-varying global–mean temperature change from a set of emissions using simplified expressions derived from the results of the comprehensive atmosphere-ocean model ECHAM4/OPYC3 (Roeckner et al., 1999). For modelling the economic damage in this thesis, damage (D) is assumed to be a simple convex function of ΔT with damage function exponent n (e. g. $D = \alpha \cdot \Delta T^n$) as common in economic analysis of climate change (Nordhaus, 1991; Kandlikar, 1995; Tol, 1999; Nordhaus and Boyer, 2000; Stern, 2007).

1.5 Outline of the thesis

The research questions are addressed in four publications while the first three form the main part of this thesis (Chapters 2 to 4). The publications analyse different design elements within physical and physic-economic metric frameworks to weigh short- and long-lived climate forcers. The article in Chapter 5 provides a more general review of the negotiation process to limit the aviation-induced contribution to climate and serves as a background analysis.

Chapter 2 derives the general form of an emission-based climate metric from basic economic principles and focuses on the economic evaluation of climate metrics. The key characteristics of any metric are used as starting point; these are (a) its impact function, i. e. its functional relationship to physical climate parameters, and (b) the weighting of impacts over time (Forster et al., 2007). In view of these characteristics the Chapter presents a physico–economic framework which facilitates a structured discussion on climate metrics since it

- provides an overview of possible options in climate metric design from meta-perspective and allows a straightforward classification of the multitude of climate metrics presented in literature.
- pinpoints assumptions and value judgements that might become relevant for the policy-maker when defining policy objectives.
- reveals simplifications that are implicit to the choice of a metric and the consequences, benefits and limits of the policy decisions,
- addresses trade-offs in uncertainties and
- outlines the leeway in decision-making.

This article has been published in *Environmental Science and Policy*[5].

Chapter 3 considers an example from practice. Changing flight altitude to avoid the formation of short-lived contrails at the expense of a counteracting long-lived effect (CO_2) is used as a generic example to illustrate how the evaluation outcome of such a trade-off depends on the selected metric type. The evaluation framework demonstrates the impact of individual physical metric choices on the preferred mitigation strategy. The concept of a turning point is established, which indicates the point in time where the mitigation of a short-term effect (e. g. line-shaped contrails) at the expense of a counteracting long-term effect (e. g. CO_2) becomes preferable. The paper discusses the benefits and limitations of the methodological approach, assesses individual metric choices and assumptions on future development, takes a critical view of the physical cost-effective metrics and highlights the role of uncertainties and common sense decisions for the policy outcome. This article has been published in *Environmental Science and Policy* [6].

In Chapter 4, three alternative types of metric-based factors are introduced to derive CO_2 equivalences for SLCF: forcing-, activity- and fossil fuel-based. A sensitivity analysis of the generic form of the economic-based CO_2 equivalence factor for SLCF highlights the implications of the non-accumulating nature of very short-lived climate forcers for the calculation of global–mean CO_2 equivalences. Step by step, the sensitivity structure of the generic CO_2e towards its input variables is analysed and the performance compared against physical-metric based CO_2 equivalences. It reveals the benefits and limitation of economic considerations in metric design in a cost-benefit rationale when weighing short- and long-lived climate effects. Finally, the generic setting is applied and extended to a specific SLCF situation, using the example of aviation-induced contrail formation. This article has been published in the journal *Climatic Change*.[7].

[5] Deuber, O.; Luderer, G.; Edenhofer O. (2013) Phyisco–economic evaluation of climate metrics: A conceptual framework. Environmental Science & Policy, 29, 37 – 45

[6] Deuber, O.; Matthes, S.; Sausen R.; Ponater, M.; Lim, L. (2013) A physical metric-based framework for evaluating the climate trade-off between CO_2 and contrails. The case of lowering aircraft flight trajectories. Environmental Science & Policy, 25, 176 – 185

[7] Deuber, O.; Luderer, G.; Sausen R. (2013) CO_2 equivalences for short-lived climate forcers. Climatic Change. doi: 10.1007/s10584-013-1014-y

Chapter 5 explores the political setting for introducing binding, globally harmonised climate targets to limit the aviation-induced contribution to climate change. Negotiating climate policies to limit emissions from international aviation has proven to be exceedingly difficult, hampering the introduction of climate mitigation strategies to internalise externalities in this sector. Sector-specific challenges caused by the non-national nature of the sector and the current institutional setting are highlighted. The section introduces possible options to include international aviation in a binding global climate regime and relates them to the negotiation positions of different actors. Special attention is paid to the global sectoral approach in international aviation coupled with the possibility of raising revenues for adaptation to climate change in developing countries. This chapter has been published as an article in the book *Emissions Trading: Institutional Design, Decision Making and Corporate Strategies*[8].

Chapter 6 presents a synthesis and conclusion.

[8]Deuber, O.: The negotiation process to include international aviation in a Post-2012 climate regime in Antes, R., Hansjürgens, B., Lethmathe, P. and Pickl, S. (2011) Emissions Trading: Institutional Design, Decision Making and Corporate Strategies. Springer Verlag. doi 10.1007/978-3-642-20592-7.

Chapter 2

Physico-economic evaluation of climate metrics: A conceptual framework

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2.1 Introduction

Effective and comprehensive multi-gas mitigation strategies as stipulated by the United Nation Framework Convention on Climate Change require climate change metrics. These represent methods for quantitatively comparing climate impacts of different radiatively active substances (e. g. Fuglestvedt et al., 2010). A multitude of emission metrics have been presented in the literature. The choice of metric type is crucially important for the numeric values of greenhouse gas exchange rates (Table 2.2, p. 32) (e. g. Boucher, 2012; Fuglestvedt et al., 2010). Identifying an appropriate metric approach for any mitigation strategy requires a clear definition and prioritization of policy objectives. Climate metric design involves physical, economic and politico-economic aspects and requires a thorough interdisciplinary perspective and understanding (Plattner et al., 2009; Shine, 2009; Godal, 2003; O'Neill, 2003; Smith, 2003). The physical sciences are indispensable in metric design for quantifying how emissions affect climate. In virtually all metric applications (e. g. emissions trading, greenhouse gas inventories, life-cycle assessments), however, explicit or implicit assumptions about the marginal utility of emission abatement of different forcing agents are made, and thus metric design also has high relevance for the field of economics.

In the past, policy-makers agreed on using a purely physical metric, the Global Warming Potential, to set up the Kyoto Protocol (henceforth GWP(H)). The IPCC introduced this metric approach but also stressed that there is no unambiguous methodology for combining all relevant factors into a single metric approach (IPCC, 1990; Shine, 2009). The GWP(H) has been subject to criticism from both natural scientists and economists (O'Neill, 2000; Fuglestvedt et al., 2003, 2010; Shine, 2009; Dorbian et al., 2011).

Most of the scientific climate metric literature assesses the rationale, the performance and limitation of certain metric types, such as physico-economic cost-benefit approaches (Eckhaus, 1992; Reilly and Richards, 1993; Schmalensee, 1993; Hammitt et al., 1996; Tol, 1999), cost-effectiveness approaches (Manne and Richels, 2001; van Vuuren et al., 2006; Reilly and Richards, 1993) or physical metrics (Lashof and Ahuja, 1990; IPCC, 1990; Gillett and Matthews, 2010; Shine et al., 2005, 2007; Tanaka et al., 2009; Peters et al., 2011). However, only few scholarly papers exist which consider metrics from a meta-perspective, including atmospheric and economic sciences. Fuglestvedt et al. (2003, 2010) provide a detailed overview of climate metric design issues. Forster et al. (2007) present a general formulation of an emission metric, based on Kandlikar (1996). Finally, Tol et al. (2012) and Johansson (2012) highlight interrelations between metric approaches. A clearly structured discussion of climate metrics along the general formulation of an emission metric is lacking.

The design of climate metrics involves explicit and implicit assumptions on the functional relationship between climate impacts and physical climate change, and the aggregation of impacts occurring at different points in time. The objective of this article is to provide a physico-economic framework which classifies the Global Damage Potential (GDP), the Global Cost Potential (GCP) and currently discussed physical metrics in a straight-forward manner. The framework, based on impact and temporal weighting functions, provides a transparent classification scheme, thus revealing underlying implicit assumptions and value judgements. Our economic interpretation of physical metrics aims to foster transdisciplinary exchange on this highly policy-relevant issue and to support decision-makers in identifying an appropriate metric, given normative judgements about the trade-off between policy targets.

Section 2.2 presents the general formulation of an emission metric. By linking it to the economic derivation of a climate metric, we develop a conceptual framework which classifies the variety of climate metrics from literature on the basis of economic rationales. The framework is established step by step in Section 2.3. Finally, Section 2.4 discusses implications of alternative metrics regarding different types of uncertainties and draws some conclusions.

2.2 General formulation of an emission metric

The starting point of the conceptual framework is a generalized formulation of an emission metric as previously introduced by Kandlikar (1996) and Forster et al. (2007). It can be written as the integral over time of the incremental weighted impact incurred by a pulse emission of gas *i*.

$$AM_i = \int_0^\infty \frac{I(CC_{ref+\Delta EM_i}(t)) - I(CC_{ref}(t))}{\Delta EM_i} \cdot W(t) \quad (2.1)$$

where the impact function *I* describes the climate impact as a function of physical climate change *CC* along a reference concentration pathway *ref*. *W* specifies the temporal weighting function. The corresponding metric value ($M_i = AM_i$ / AM_{CO_2}) refers to the impact of 1 kg of emission *i* (ΔE_i) normalized to the one of 1 kg reference gas, usually CO_2 (ΔEM_{CO_2}). *I* and *W* are crucial determinants of the metric value M_i, and can be used to characterize alternative metrics.

2.2.1 Impact function

The impact function *I* relates the metric to a climate impact proxy in the chain of impacts, such as global mean radiative forcing *RF*, the change in global mean temperature ΔT or economic damage (Hammitt, 1999; Fuglestvedt et al., 2003; van Vuuren et al., 2006; Plattner et al., 2009). In some cases, the rate of change of a climate impact parameter is also used as proxy. An ideal metric would consider the entire causal chain of impacts. Since, however, the last step, quantifying damages as a function of physical impact parameters, is subject to large scientific and value-based uncertainties, (e. g. Forster et al., 2007; Wuebbles et al., 2010; Stern, 2007; Hanemann, 2010), it is common to make simplifying implicit assumptions about the interrelation between economic damage and physical impact and apply physical climate parameters as an impact proxy. Further, the assumed future concentration pathway is an important aspect of the impact function. The impact function *I* in the generalized formulation of an emission metric (Eq. 2.1) refers to a pulse emission. Some approaches, however, calculate metric values based on sustained emissions or an emission scenario over an extended period of time (Shine et al. e. g. 2005 and Chapter 3. Sustained emission metrics can be derived from pulse emission metrics through convolution (see e. g. Boucher, 2012). For the sake of conceptual clarity, we focus our analysis on pulse emissions.

2.2.2 Weighting function

The weighting function *W* aggregates impacts occurring at different points in time. The following three variants are commonly used in climate metric design (Section 2.3.3, Fig. 2.1b)[1].

- (a) the exponential weighing function $W(t) = r \cdot e^{-rt}$, corresponding to the discount function commonly used in economics for aggregating monetary values over time with a discount rate *r*, given in % per year;

[1] We normalized the weighting functions such that $\int_0^\infty W(t)dt = 1$.

- (b) the unit step function (θ-function, e. g. (Boas, 2006))

$$W(t) = \frac{1}{H} \cdot \theta(H - t) = \begin{cases} 1/H & for\ t \leq H \\ 0 & for\ t > H \end{cases} \tag{2.2}$$

  which assigns equal weight to all impacts occurring over a finite time horizon H; and

- (c) the Dirac Delta function (δ-function, e. g. (Boas, 2006))

$$W(t) = \delta(t_x) - t = 0\ for\ t \neq t_x\ with \int_{-\infty}^{\infty} F(t)\delta(t_x - t)dt = F(t_x) \tag{2.3}$$

  which only evaluates the impacts at one discrete point in time t_x (end point weighting).

For each of these weighting functions, free parameters exist that determine the time scale of evaluation: the discount rate r (discounting), the time horizon H (θ-function) and the end point (t_x) (δ-function). Again, the choice of these time frame parameters involves normative decisions. In most metric approaches they are taken as constant. Some physical metrics exist, however, in which the time frame parameter is replaced by the distance between the point in time of emission release and a specific target year (e. g. Berntsen et al., 2010; Shine et al., 2007; Tanaka et al., 2009).

2.3 Characterizing climate metrics

In the following, we establish a conceptual framework by characterizing alternative metric choices based on the applied impact and weighting function. In Section 2.3.1 we demonstrate how the Global Damage Potential is derived from first economic principles. Other metrics can be interpreted as variants of this benchmark approach (Section 2.3.2). The synthesis provided in Section 2.3.3 reveals the implicit assumptions underlying the alternative approaches and highlights interrelations across the metric types.

2.3.1 The first-best approach: Global Damage Potential

The concept of marginal impacts from emission pulses, which serves as a basis for the definition of the absolute metric (Section 2.2), is grounded in the cost-benefit analysis, building on marginal climate change impacts and marginal costs of emission reductions. An economically optimal abatement strategy implies that the sum of mitigation and damage costs assumes a minimum. In our case of greenhouse gases with varying atmospheric lifetimes, this means that the discounted present value of marginal abatement costs (MAC) of an emission of

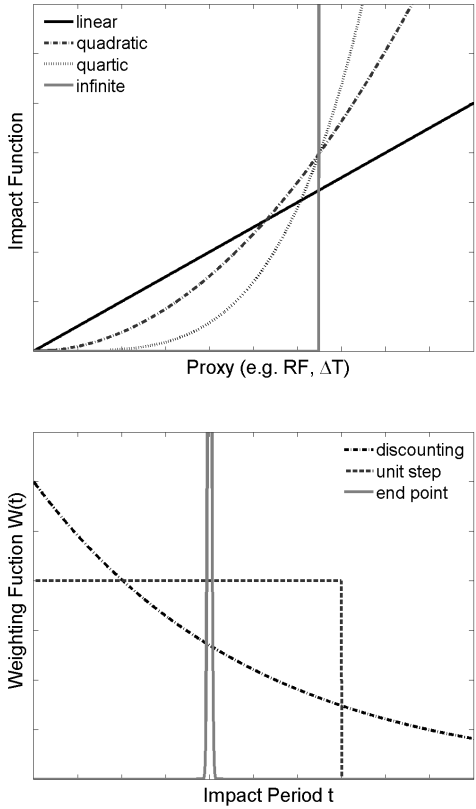

Figure 2.1: *Schematic representation of commonly used (a) impact functions and (b) temporal weighting functions. All physical metrics assessed in this study use linear impact functions, while impact functions considered for the GDP typically include non-linear convex functions. The GCP implicitly considers zero impacts below the climate threshold and infinite impacts above. Physico-economic metrics typically use exponential discounting for the temporal weighting function, while unit step and end-point weighting is more commonly used in physical metrics.*

agent I has to be equal to the marginal discounted present value of damage costs (MDC) of the same emission;

$$MAC_i = MDC_i \tag{2.4}$$

In the case of CO_2, these *MDCs* are often referred to as the social costs of carbon and correspond to the optimal (Pigouvian) tax level (Pigou, 1932; Baumol, 1972; Nordhaus, 1991; Fankhauser, 1995).

In view of uncertainty about the *MACs*, it is not possible for policy-makers to define ex ante optimal abatement levels for each individual greenhouse gas. Instead, emissions can be regulated by introducing a cap for the total emissions and assigning an emission metric to each individual gas, thus letting the market decide how best to achieve the total emission constraint ('what flexibility'). An optimal climate metric is one that relates the marginal costs of emission control to the future stream of damages of climate change avoided by that emission reduction.

In this case, the metric M_i of a pulse emission I equals its potential climate impact (also referred to as absolute metric AM_i normalized to the impact incurred by a reference gas (usually carbon dioxide (CO_2, AM_{CO_2}), see for a detailed mathematical framework Tol et al. (2012).

$$M_i^D = \frac{AM_i}{AM_{CO_2}} = \frac{MDC_i}{MDC_{CO_2}} \stackrel{!}{=} \frac{MAC_i}{MAC_{CO_2}} \tag{2.5}$$

By establishing a ratio of *MDCs* the scaling factor from physical impact to economic costs including the related uncertainties cancels out; solely the functional form of the economic damage function remains relevant. The requirement in Eq. 2.5 that the metric be equal to the ratio of *MACs* arises directly from the efficiency condition (Eq. 2.4). The corresponding first-best metric approach from a socio-economic point of view is the Global Damage Potential (GDP, Eckhaus 1992; Kandlikar 1996; Tol 1999). The GDP, also named Economic Damage Index (EDI, Hammitt et al. 1996), is based on the evaluation of the future stream of discounted economic damages.

$$GDP : M_i^D = \frac{\int_0^\infty \partial D/\partial EM_i \cdot \Delta EM_i \cdot e^{-rt} dt}{\int_0^\infty \partial D/\partial EM_{CO_2} \cdot \Delta EM_{CO_2} \cdot e^{-rt} dt} \tag{2.6}$$

Typically, exogenous scenario assumptions on future atmospheric background greenhouse gas concentrations are taken. Beyond predicting changes in physical parameters, the fundamental challenge in GDP calculation consists of determining the functional form of the damage function, which relates economic damages to changes in physical impact parameters. In economic analysis of climate change it is most common to assume damage to be a convex function of ΔT (e. g. $D = \alpha \cdot \Delta T^n$) (Nordhaus, 1991; Kandlikar, 1995; Tol, 1999; Nordhaus and Boyer, 2000; Stern, 2007) while some approaches (e. g. Hammitt et al., 1996; Tol, 2003) additionally consider potential discontinuities.

Even though in economic literature there is a rough conception of the functional interrelation between economic damage and physical climate impact parameter, it is very challenging to quantify damages. It is characterized by a high degree of scientific uncertainty since it requires a full representation of the relevant complex causal relationships, including a down-scaling of global changes to the regional and local level (Hanemann, 2010). On the other hand, valuing climate impacts is closely related to questions of irreversibility and inter- and intragenerational equity and requires value judgements, in particular with regards to the aggregation of impacts across regions and over time, as well as the treatment of non-market impacts (Tol, 2005). The economic evaluation of non-market goods such as ecosystem loss, climate amenity, health and higher mortality risks is strongly controversial (e. g. Stern, 2007).

In climate metric design, handling uncertainty with respect to the functional form of the economic damage function is the key motivation to refrain from the theoretically optimal cost-benefit approach. Specific assumptions are taken to simplify the case ('second best approaches' Tietenberg 1992).

2.3.2 Classification of other metric approaches

There are two fundamentally different second-best approaches to avoid the uncertainty associated with the functional form of the economic damage: physical metrics use impact functions that are based on physical climate variables, whereas cost-effectiveness approaches calculate economically optimal exchange rates between greenhouse gases given a prescribed climate target. Both approaches are discussed in the following.

Physical metrics

Physical climate metrics avoid the perils of economic evaluation by choosing a physical impact proxy that is located further upstream in the chain of impacts (ΔT or RF), implicitly assuming linearity between economic damage and physical impact proxy. The uncertainty affecting metric calculation is thus reduced to uncertainties related to the physical processes of the climate system, e. g. the carbon cycle, atmospheric chemistry interactions and radiative effects (RF as proxy), as well as the climate sensitivity and the time scale of the climate response (ΔT as proxy) (Fuglestvedt et al., 2003, 2010; Forster et al., 2007). Simplifications are achieved by assuming a specific background concentration pathway C_{ref}.

A multitude of temperature-based metrics are proposed in literature: They differ in their choice of W, time frame parameter and C_{ref}. The Global Temperature Change Potential applies the δ-function, referring either to a pulse or a sustained emission with a constant end point t_x (t_x =const) ($\mathrm{GTP_p}$, $\mathrm{GTP_s}$) (Shine et al., 2005), or to a pulse emission with a time-dependent end point representing the distance between the time of emissions release t_0 and the time t_{tar} at which a specific climate target is expected to be reached ($t_x = t_x(t_0, t_{tar})$) ($\mathrm{GTP_p}(t)$, Shine et al. 2007). The Mean Global Temperature Potential MGTP(H) (Gillett and Matthews, 2010), in contrast, applies the θ_∞-function for weighting. The MGTP(H), GTP_p and $GTP_p(t)$ in their original versions assume constant atmospheric conditions ($C_{ref} = C_{ref}(t_0)$). However, the $GTP_p(t)$ refers indirectly to an exogenously determined emission scenario via the shortening of the time horizon over time ($t_x = t_x(t_0, t_{tar})$). It suggests itself that the exogenously determined scenario can also be used as C_{ref}, see e. g. Chapter refchap:3.

RF-based metrics, such as the GWP(H), relate generally to a defined constant atmospheric state. The GWP(H) applies the θ-function and assumes constant atmospheric condition of the emission year ($C_{ref} = C_{ref\ (t_0)}$ (IPCC, 1990). Its physical and economic performance is well analysed, (e. g. Forster et al., 2007; Johansson et al., 2006; O'Neill, 2003), including its physical uncertainties related to atmospheric sinks (Reisinger et al., 2010; Manning and Reisinger, 2011). The original version of the GWP (henceforth: GWP(r)) (Lashof and Ahuja, 1990), in contrast, discounts the impacts and considers an average forcing value over possible future ranges in concentration ($C_{ref} = C_{\mathrm{ref}(\varnothing \mathrm{future})}$) to account for the non-linearities in the concentration-forcing relation. The Economic Global Warming Potential EGWP (Wallis and Lucas, 1994), a formally extended form of the GWP, additionally covers the rate of change of atmospheric forcing. In its two variants, it uses either the θ-function or discounting for inter-temporal aggregation. The Temperature Proxy Index TEMP (Tanaka et al., 2009; Shine, 2009) offers a slightly different perspective: it describes the optimal gas-dependent time horizon H for the GWP(H) as a result of a tuning process with respect to historical RF and temperature development. The Forcing Equivalent Index FEI (Manning and Reisinger, 2011; Wigley, 1998), a similar approach, was also designed to reproduce a historical pathway of RF.

Global Cost Potential

The GDP is grounded in the cost-benefit analysis, building on marginal climate change impacts and marginal costs of emission reductions. In view of the large uncertainty associated with economic evaluation of climate impacts, and the possible existence of discontinuous changes in the earth's climate system (or 'Tipping Points', cf. Lenton et al. 2008), the cost-effectiveness framework is proposed as an alternative to the cost-benefit approach (Markandya et al., 2001): 'guardrails' or 'tolerable windows' for one or several climate variables such as ΔT or the rate of temperature change are adopted as boundary conditions for climate mitigation strategies (Petschel-Held et al., 1999; Bruckner et al., 1999). A prominent example of the cost-effectiveness approach is the objective to avoid dangerous anthropogenic interference with the climate system by keeping global warming below 2 °C, a target which is widely accepted in the international climate policy community (Copenhagen Accord), (e. g. Meinshausen et al., 2009). Also, the vast majority of climate change mitigation scenarios are based on a cost-effectiveness approach (Fisher et al., 2007).

Analytically, cost-effectiveness approaches can be treated as special cases of the cost-benefit analysis in which the damage cost curve (D) is implicitly assumed to be zero within the 'tolerable window' and to diverge to infinity at a physical impact threshold PI_{thres} (θ_∞-function):

$$D(PI) = \theta_\infty(PI - PI_{thres}) = \begin{matrix} 0 & for\ PI < PI_{thres} \\ \infty & for\ PI \geq PI_{thres} \end{matrix} \quad (2.7)$$

In the hypothetical case of CO_2 as the only greenhouse gas, the optimal carbon price would emerge as MAC at the pre-defined climate threshold. While cost-effectiveness approaches are primarily designed for the derivation of global emission targets, they have peculiar implications for the derivation of metrics, which are an inherently marginal concept. In cost-effectiveness approaches, marginal damages are implicitly assumed to be zero below the climate target and infinitely large at the threshold. While Eq. 2.4 (Section 2.3.1) cannot be evaluated in this case, one can take advantage of the condition that for cost-optimal climate policy, the metric also has to be equal to the ratio of $MACs$. This gives rise to the Global Cost Potential (GCP) (Kandlikar, 1996; Tol et al., 2012; Johansson, 2012), also referred to as 'price ratios' (Manne and Richels, 2001):

$$M_i^{CE} = \frac{MAC_i^{PI_{thres}}}{MAC_{CO_2}^{PI_{thres}}} \quad (2.8)$$

The GCP is given by the ratio of two gases' $MACs$ least cost emission trajectory maintaining a prescribed climate target. Typically, the physical impact threshold PI_{thres} is either expressed in terms of ΔT (e. g. Manne and Richels, 2001) or RF (e. g. van Vuuren et al., 2006).

2.3.3 Synthesis

Using our conceptual framework, the prevalent metrics can be categorized unambiguously according to their choice of impact and weighting function (Table 2.1). The impact proxy is the most pivotal element of a metric and therefore serves as a primary classification criterion. The GDP considers economic damage as impact proxy which is in general a non-linear function of the physical state of the climate and subject to substantial uncertainty (Fig.2.1a). As elaborated in Section 3.2.1 and illustrated in Fig.2.1a, purely physical climate metrics take a simplifying approach by (using physical climate parameters as an impact proxy, thus) implicitly assuming a linear relationship between economic damage and physical impact proxy ΔT (GTP_p, MGTP, TEMP), RF (GWP(r), GWP(H), FEI, or RF and the change of RF (EGWP). An alternative group of metrics is based on cost-effectiveness approaches, thus implicitly assuming damages to be zero below a certain temperature GCP(ΔT) or forcing threshold GCP(RF), cf. Section 2.2.2 and Fig.2.1a.

The second important dimension in metric design is the choice of temporal weighting function (Fig. 2.1b). All physico–economic metrics and some physical metrics use exponential discounting for aggregating impacts over time. Al-

Impact function I			Weighting function W		
Impact proxy	**Implicit damage function**	**Atmospheric background (C_{ref}, *specification*)**	**Discounting** **discount rate r**	**constant** **θ-function** **time horizon H**	**End point** **δ-function** **end point t_x**
D	$D = F(\Delta T)$	scen, *exogenous*	GDP		
ΔT	$D = \theta_\infty(\Delta T - \Delta T_{thres})$	scen, *endogenous*	GCP(T)		
ΔT	$D \propto \Delta T$	scen, ref_{t_0}		MGTP	
ΔT	$D \propto \Delta T$	scen, ref_{t_0}			GTP
ΔT	$D \propto \Delta T$	scen, *ref(historical)*		TEMP	
ΔT	D=$\theta_\infty(RF - RF_{thres})$	scen, *endogenous*	GCP(RF)		
RF	$D \propto RF$	scen, ref($\varnothing future$)	GTP(r)		
RF	$D \propto RF$	scen, ref_{t_0}	GWP(H)		
RF	$D = \gamma \cdot RF + \omega \cdot \partial RF/\partial t$	const, ref_{t_0}	EGWP		
RF	$D \propto RF$	scen, *historical*		FEI	

Table 2.1: *Classification of climate metrics. The impact function I specifies the selected climate impact proxy including the underlying damage function and C_{ref} (scenario (scen), constant (const), specifications see text). The weighting function W is characterized by the type of weighting function and the relevant time frame parameter r, H or t_x, respectively (specification see text).*

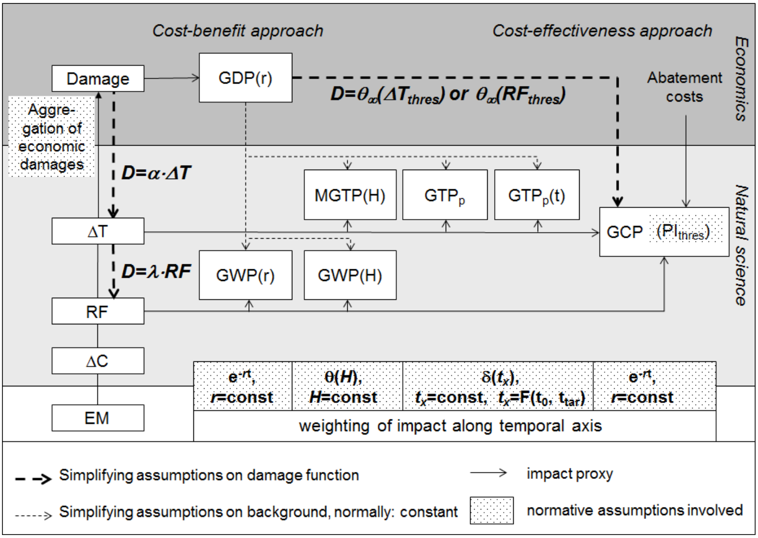

Figure 2.2: *Interrelation between the GDP and selected physical and physico–economic metric approaches (GWP, MGTP,* $\mathrm{GTP_p}$*,* $\mathrm{GTP_p}(t)$ *and GCP) highlighting the underlying policy objective, impact proxy, weighting function and respective scientific discipline.*

ternative approaches are unit step functions (GWP(H), MGTP, TEMP, FEI) or end-point weighting ($\mathrm{GTP_p}$, $\mathrm{GTP_p}(t)$).

As in the GCP metrics, the $\mathrm{GTP_p}$ is based on the cost-effectiveness rationale. In fact, the $\mathrm{GTP_p}(t)$ was designed to provide an easy-to-calculate alternative to the GCP and indeed yields similar metric values (Shine et al., 2007). This can be understood from the fact that both approaches only consider the long-term effect of emissions, either by explicitly assuming a temporal weighting function that excludes the short and medium time-scales (as in the case of the $\mathrm{GTP_p}$), or by assuming an impact function that is non-zero only in the distant future (as in the case of the GCP). In more formal terms, it can be shown that the GTP is a special case of the GCP if abatement costs in different periods can be assumed to be independent (Tol et al., 2012). The cost-effective temperature potential (CEPT), which by construction of its temporal weighting function only considers climate impacts that occur after the climate target has been reached, is a physical metric that can almost exactly reproduce the behaviour of the GCP (Johansson, 2012).

The conceptual framework illustrates the interrelations between different metrics (Fig.2.2). It shows that alternative metrics can be constructed as variants of the GDP. For all metrics, normative judgements are involved in the choice of the time frame parameter, be it the discount rate r in the context of exponential discounting, the time horizon H in unit step aggregation or the end-point t_x. In the case of the physico–economic metrics, further normative assumptions are relevant in the derivation of the damage function or the choice of the climate target PI_{thres}.

2.4 Discussion and conclusion

Our conceptual framework illustrates that metric approaches can be classified unambiguously according to their implicit assumptions about the impact and temporal weighting function. For a metric to be optimal from an economic point of view, it must be based on the evaluation of marginal economic costs incurred by emissions. The GDP follows this basic rationale, and thus would ensure – absent uncertainty – multi-gas abatement strategies to be cost-optimal for a given set of normative assumptions.

As shown in Section 2.3.3, the vast majority of metrics used in the literature can be constructed as variants of the GDP. Also the guardrail approach used in a cost-effectiveness framework can be seen as special case of the GDP in which damages are assumed to grow to infinity at a particular climate threshold. Given (a) its property of economic efficiency, and (b) its flexible formulation of the damage function, which allows establishing all other metrics as variants of it, the GDP is uniquely positioned and can be used as a reference point for the evaluation of metrics.

The paramount challenge in the design of metrics is to deal with uncertainty. Following Dorbian et al. (2011), and with partly different definitions than in Plattner et al. (2009), we distinguish between the following types of uncertainties:

- *value-based uncertainty*, the degree to which normative judgements are involved,
- *scientific uncertainty*, uncertainty in the knowledge about the underlying processes in the causal chain between emissions and impact function,
- *scenario uncertainty*, the degree to which the metric depends on the future states of the world, e. g. atmospheric background conditions, and
- *structural uncertainty*, the degree to which the metric represents the policy–relevant real world trade-offs.

While the first three types of uncertainties are of explicit nature with a direct link to operational feasibility, the latter takes effect implicitly. The choice of metric is largely characterized by trade-off between different kinds of uncertainties. This can be illustrated by comparing the GWP– and GDP–metrics. The key advantage of the GWP(H) lies in the fact that (a) the value-based uncertainty is reduced to the choice of time horizon, (b) the scientific uncertainty is kept to a manageable level by only considering the causal chain between emissions and forcing, and (c) the scenario uncertainty is eliminated by assuming constant background conditions. On the other hand, the GWP is characterized by rather high implicit structural uncertainty and low policy relevance, since there is no direct link between *RF* and climate damages, and likewise, future atmospheric background conditions will not remain constant.

In this respect, the GDP is distinctly different from the physical metrics. As elaborated above, it ensures economic efficiency, thus it accurately represents real-world trade-offs and features low implicit structural uncertainty. This comes, however, at the expense of more explicit uncertainty: (a) high value-based uncertainty as, in addition to the choice of discount rate, normative judgements are involved in the valuation and aggregation of damages, (b) higher scientific uncertainty as the entire causal chain from emissions to damages is represented, and (c) scenario uncertainty as we are unsure about the future state of the world.

Table 2.2 provides an indicative overview of how metrics perform in terms of different uncertainty categories. It further demonstrates numerically some explicit uncertainties, using the example of CO_2 equivalences for methane. Generally speaking, physico–economic metrics are characterized by lower structural uncertainty which in principle makes them most policy relevant and more flexible to adjust to our knowledge of climate change and its impacts. This feature comes at the expense of higher scientific, value-based and scenario uncertainties (wider range of possible metric values). Physical metrics, in contrast, have high structural but lower value-based, scientific and scenario uncertainties (smaller range of possible metric values).

While economic efficiency and environmental effectiveness are the most crucial evaluation criteria, it is important to note that for any practical policy application, simplicity and transparency are also important (Fuglestvedt et al., 2003, 2010; Wuebbles et al., 2010). So far, the GWP, simple and transparent and thus easy to operationalize, has been the metric of choice for policy applications. In this metric, many of the relevant uncertainties are concealed by simplifying structural assumptions. While physico-economic metrics such as the GDP are much more difficult to operationalize, it can be seen as their advantage that they make the relevant uncertainties explicit. As an alternative approach to the use of simplifying physical metrics, policy-makers could consider a GDP-based approach, in which the relevant value judgements and assumptions are considered in a direct and transparent manner (see e. g. Hammitt et al., 1996; Dorbian et al., 2011; Boucher, 2012).

Particularly with regard to the interdisciplinary retrial of climate metrics stipulated in the scientific literature, (e. g. Shine, 2009) and on the level of the IPCC (Plattner et al., 2009), the conceptual framework provides a valuable basis for discussions, since it allows scientists and policy-makers to disentangle and compare relevant implicit and explicit assumptions in a transparent way. As the framework elucidates the relationship between physical metrics and more comprehensive metrics that include the economy, it may help to enhance the scientific discourse between researchers from different climate research communities.

Metric	explicit uncertainties			implicit uncertainties		CO_2eq. for CH_4 (examples)[a]
	scientific	value-based	scenario	structural	median[b]	uncertainty range[c], (standard deviation)
GWP	•	••	•	•••••	27.2	22.5 – 32.5 (2.8)
GTP	••	••	••	••••	6.2	4.5 – 9.0 (1.8)
GCP(*RF*)	••	•••	••	•••		
GCP(ΔT)	•••	•••	••	••		
GDP	•••	••••	••	•	26.3	15.0 – 40.0 (6.7)
	Increasing operationalizability with decreasing uncertainty			Increasing policy relevance with decreasing uncertainty		
	Implications for policy applications					

[a]Boucher (2012).

[b]100-year GWP, 100-year GTP_p and GDP, include the conversion of CH_4 into CO_2.

[c]90 % confidence interval.

Table 2.2: *Commonly used metric approaches: Indicative and qualitative assessment of different kinds of uncertainties (uncertainty increases with number of bullet points). Exemplary CO_2 equivalences for methane illustrate the range of possible values.*

Chapter 3

Metric-based framework for evaluating the climate trade-off between CO_2 and contrails

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3.1 Introduction

The design of multi-gas emission mitigation policies requires climate metrics, which are methods for quantitatively comparing the global climate impact of different climate change mechanisms. An optimal metric, however, is not obvious (Shine, 2009; Fuglestvedt et al., 2010). Particularly, when evaluating short-lived and long-lived climate effects (Fuglestvedt et al., 2010; Shine et al., 2005, 2007) or corresponding trade-off situations (Boucher and Reddy, 2008; Peters et al., 2011), the outcome of mitigation policies depends crucially on the selected metric. Scientific and political challenges must be overcome in order to include short-lived climate effects in multi-gas strategies (Rypdal et al., 2005).

The need for an approved methodological framework has become notably apparent in the aviation sector. Aviation contributes to climate change not only by the emission of the long-lived greenhouse gas CO_2 but also, significantly, by induced short-lived ozone and cloudiness (Lee et al., 2009, 2010). Various conceptual approaches to weigh these climate effects exist (e. g. Marais et al., 2008; Fuglestvedt et al., 2010; Dorbian et al., 2011; Azar and Johansson, 2011). An accepted metric, however, is still lacking (Wit et al., 2005a; Forster et al., 2006), which delays the design of non-CO_2 climate policies.

By means of a generic trade-off situation in aviation, we propose an evaluation framework which systematically compares the influence of crucial methodological assumptions in physical metric design on the evaluation of short- and long-lived climate effects. We limit our approach to consider only climate impacts on a global level at this stage, being aware that the trade-off on the regional scale may be different due to a different response structure (e. g. Rap et al., 2010). Metrics including the inhomogeneity of climate responses are still in its infancy (Rypdal et al., 2005; Lund et al., 2012), but may be available for optimised policy decisions at a later stage. Contrail mitigation by lowering flight trajectories globally at the expense of a fuel penalty is singled out as an example. Contrails are line-shaped ice clouds that form behind an aircraft when hot and moist exhaust gases mix with cold and sufficiently humid ambient air and saturation with respect to liquid water is reached (e. g. Schumann, 2005). Contrails may persist and transform to contrail cirrus (Burkhardt and Kärcher, 2011). Avoiding ice-supersaturated areas by flight re-routing has been identified as one of the most promising options to mitigate contrails (Sausen et al., 1998; Fichter et al., 2005; Mannstein et al., 2005; Gierens et al., 2008).

This article analyses when it is favourable to mitigate contrails, which develop and persist on a time scale of hours, at the expense of CO_2 concentration changes whose impact is relevant for centuries due to the long atmospheric lifetime of CO_2. The evaluation outcome of such a trade-off situation depends on the selected metric, which implies several policy decisions (see Deuber et al., 2013a, and Chapter 2, respectively), including

- The definition of the policy objective, e. g. to minimise the sum of mitigation and damage costs (cost benefit approach (CBA) e.g. Hammitt et al. 1996) or to keep climate in a cost-effective manner within pre-defined bounds (cost-effectiveness approach (CEA) e. g. Manne and Richels 2001);
- The weighting of impacts along the temporal axis and the specification of an adequate proxy for climate change (Hammitt, 1999), which we define here as metric choices;
- The assumptions on the future background concentration pathway;
- The aviation emission type, i.e. the emission situation is considered as single event (pulse) or as part of a specific future aviation development (sustained or scenario emissions).

This article introduces the concept of a 'turning point'. The latter marks the point when the respective metric recommends a change of strategy. We apply metrics which provide 'equivalence' in climate impact within a chosen time frame ('physical cost-benefit metrics') and others which aim to weigh gases along a specific concentration pathway relative to a climate target ('physical cost-effective metrics') (Fuglestvedt et al. 2003; Shine et al. 2007; Azar and Johansson 2011). We assess the global warming potential (GWP) (e. g. Fuglestvedt et al., 2003), the global temperature (change) potential for a pulse emission (GTP_p) (Shine et al., 2005), the mean global temperature potential (MGTP) (Gillett and Matthews, 2010) and the time-dependent GTP in the context of a climate target ($GTP_p(t)$) (Shine et al., 2007) and establish a comprehensive metric-based evaluation framework.

The computed turning points, which are a function of the selected metric, reveal how sensitive the trade-off assessment is with respect to the policy objective, the metric choices, the assumption on the future concentration pathway, the aviation emission type and, finally, by parametric uncertainties.

3.2 Methodology

3.2.1 Trade-off situation

Our generic trade-off situation between CO_2 and contrails is defined by a base and contrail mitigation case, adopting a methodology established in the EU Project TRADEOFF (e. g. Gauss et al., 2006). The base case reflects the flight profile of typical global aircraft movements for the year 2000. In the contrail mitigation case the cruise altitude of each flight profile is displaced to a 6000 ft lower flight level, resulting in a fleet-average fuel penalty of approximately 6 %. This relative fuel penalty is held constant for future projections. The change of flight levels leads to a reduction of the global mean RF of contrails by a factor of roughly 50 % (Fichter et al., 2005).

For a straightforward presentation we focus solely on CO_2 and contrails, excluding other important climate effects such as the reduction in the global mean climate impact of NO_x emissions through ozone when flying at lower altitudes (e. g. Frömming et al., 2012). For illustrative purposes we selected a mitigation case involving a *substantial* change in flight trajectory. Changes in total net RF from contrails decrease almost linearly with a lowering of flight altitude, while those caused by additional CO_2 emissions show a gradual, i. e. monotonic increase (Frömming et al., 2012, Fig. 10). We therefore expect, in principle, the same sequence of turning points as function of metric type for smaller displacements of flight trajectories.

The *global* shift of flight trajectories includes also displacements where no contrails are mitigated, no contrails would form anyway or where even additional contrails might form. Our simplified mitigation example is selected to highlight the consequences of policy decisions on the trade-off assessment. In practice a contrail mitigation strategy is more complex i. e. *individual* flight trajectories may be modified based on a more sophisticated analysis of regional and seasonal effects or meteorological conditions or even actual weather conditions, where relatively small flight altitude changes can be sufficient to mitigate a large fraction of the impact (e. g. Mannstein et al., 2005; Gierens et al., 2008; Azar and Johansson, 2011; Schumann et al., 2011; Frömming et al., 2011).

3.2.2 Metric-based evaluation of the turning point

Climate metrics

Any metric is characterised by its impact function *I(t)*, a measure to quantify the climate impacts along a specific reference concentration pathway, and by the weighting of the impacts over time, the weighting function *W(t)* (Forster et al., 2007; Deuber et al., 2013a, and Chapter 2, respectively). GWP, MGTP, GTP_p and $GTP_p(t)$ (definitions see Appendix Eq. A.1 – A.3 p.117), hereafter designated as standard metrics, contain a physical impact parameter: GWP uses radiative forcing (*RF*), while MGTP, GTP_p and $GTP_p(t)$ are metrics relating to the change in global mean temperature (ΔT) as proxy. GTP_p describes the climate impact at a certain point in time (end point metric, Table A.1, p.119; Eq. 2.3, p. 22), while GWP and MGTP provide average mean values (average metrics), (Table A.1,p. 119; Eq.2.2, p. 22). Further, our physical cost-benefit standard metrics (e. g. GWP, MGTP and GTP_p) assume constant atmospheric background conditions and integrate over a constant time horizon *H*. In contrast, our physical cost-effective metric $GTP_p(t)$ considers the distance D^{tar} to a climate target (e. g. the 2 °C target) and takes into account the corresponding future climate stabilisation pathway; here we consider the Representative Concentration Pathway RCP2.6 (Section 3.2.5).

Within our evaluation framework we test several set-ups for metrics in a way that one test differs from another solely in one aspect, either a feature of weighting or impact function (Table A.1, p. 119). Beyond the standard definition of metrics, we extend the framework to physical cost-effective metrics by considering either an average mean weighting function or *RF* as a proxy for climate change ($MGTP_p(t)$, $GWP_p(t)$). In the physical cost-benefit framework we additionally account for assumptions on time-varying atmospheric conditions and for sequences of aviation emissions (Section 3.2.5). For the latter, we follow (Shine et al., 2005) to calculate the GTP of sustained emissions (GTP_s) and transfer the methodology to other metric choices ($MGTP_s$, GWP_s). Respective metrics referring to specific aviation scenarios are accordingly calculated ($MGTP_s^{RCP6.0}$, GWP_{scen}).[1] Generally, the indices in our metric nomenclature $M^{background}_{emission\ type}[i](t)$ refer to the atmospheric background conditions and the aviation emission type for the considered cases *I* (base case: *base*; contrail mitigation case: *cmc*) with $t = H$ indicating physical cost-benefit and $t = D^{tar}$ representing physical cost-effective metrics.

No direct relationship between an aviation emission and the resulting contrail forcing exists. For simplicity, we assume that the contrail RF is a linear function

[1] We are aware that this does not produce metrics in the established sense as with reference to a specific aviation scenario universal validity is no longer applicable.

of the global mean fuel burn (Gierens et al., 1999; Forster et al., 2006; Fuglestvedt et al., 2010).

The turning point

As the crucial parameter for our evaluation framework we define the 'turning point' T_{TP} at which one case becomes preferable to the other. Formally, it represents the time when the emission-based climate effects CI[i] of the two considered cases i become equal, their ratio R (Eq. 3.1) becoming 1. CI[i] is calculated by means of the CO_2 emissions of the respective case $EM^{i}_{CO_2}$ and the contrail metric according to Eq. 3.1:

$$R(t) = \frac{CI[cmc](t)}{CI[base](t)} = \frac{EM^{cmc}_{CO_2} + EM^{cmc}_{CO_2} \cdot M[cmc](t)}{EM^{base}_{CO_2} + EM^{base}_{CO_2} x M[base](t)} \tag{3.1}$$

The turning point is a function of the selected metric *M[i](t)* including its intrinsic parameters. It comprises the response characteristics of the climate system for the generic mitigation problem, quantifies the dependency on different underlying assumptions and choices, and eventually provides a transparent basis for decision making in each of the policy frameworks:

- Within the physical cost-benefit framework the turning point marks a specific time ($T = T_{TP}$). If the policy-maker chooses to minimise the climate impact over a specific evaluation horizon H_{cba}, which is smaller than T_{TP}, the contrail mitigation case is assessed as favourable, otherwise the base case (Fig. 3.1a).
- Within the physical cost-effective framework the turning point indicates a specific distance to a target ($T_{TP} = D^{TP}_{tar}$). If the policy-maker evaluates the trade-off situation at a time prior to D^{TP}_{tar}, the contrail mitigation case is preferential, otherwise the base case (Fig. 3.1b).

3.2.3 Model description

Radiative forcing and temperature response from aviation emission scenarios, the physical basis for our metric calculation, are computed by means of the linear response model LinClim (Lim and Lee, 2006). The modelling approach is based upon Hasselmann et al. (1997); Sausen and Schumann (2000). LinClim reproduces the global mean transient behaviour of the comprehensive atmosphere–ocean model ECHAM4 OPYC3 (Roeckner et al., 1999). It has a standard climate sensitivity parameter λ_{CO_2} of 0.64 K/Wm^{-2} and a time scale of the climate response τ of 37.4 a. As user choice, we apply a contrail efficacy of r_{con} of 0.59 (Ponater et al., 2005). The future concentration pathway, the underlying aviation scenario, and the considered time range also form a necessary, user defined, simulation input. In LinClim, by standard, the global mean RF from line- shaped contrails of 10 mW m^{-2} a for the year 2000 (Sausen et al., 2005) is attributed to the

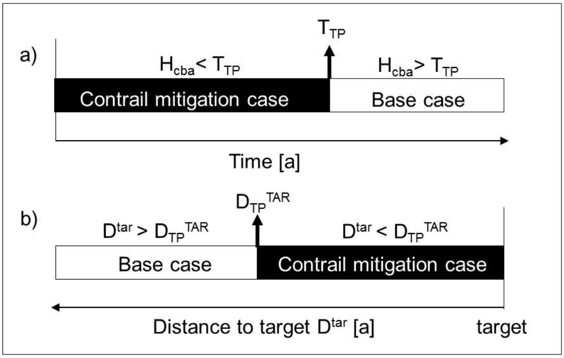

Figure 3.1: *Schematic display of the decision on the preferred case (base case, contrail mitigation case) based on the concept of the turning point: a) physical cost-benefit approach (T_{TP}), b) physical cost-effective approach (D_{tar}^{TP})*

corresponding annual fuel consumption of 214 Tg a^{-1} (IEA, 2006). The contrail RF scales linearly with fuel burn. An additional factor accounts for disproportionate future traffic growth in the upper troposphere and increasing propulsion efficiency of aircrafts (Gierens et al., 1999).

3.2.4 Sensitivity analysis

The model parameters λ_{CO_2} and τ and the contrail efficacy parameter r_{con} have a large uncertainty due to insufficiently understood processes and feedbacks (e. g. Forster et al., 2007). To analyse the effects of this parametric uncertainty on our physical cost-benefit metric-based results we take into account the lower and upper range of the parameters from literature (λ_{CO_2} between 0.5 and 1.2 K/Wam^{-2}; τ between 10.7 a and 50 a (Forster et al., 2007); and r_{con} between 0.3 (Rap et al., 2010) and 1) and vary them by a set of sensitivity tests. Additionally, we consider a 'contrail cirrus mitigation case', in which also some fraction of contrail cirrus and its RF is avoided by the assumed displacement of aircraft movements. We quantify the base case by an aviation-induced cloud RF of 30 mW m^{-2} a in 2000, approximating mean values from literature (Lee et al. 2009; Burkhardt and Kärcher 2011), and assume the same contrail reduction factor and efficacy as in the contrail case.

3.2.5 Further input data

Our standard metrics consider pulse aviation emissions as they imply generality, i. e. they are straightforward in putting the different characteristics of various forcing agents to a common scale. To account for a specific future aviation development, we additionally consider sequential pulse emissions, whose effects can be regarded as additive: (a) a pulse aviation emission in 2000 and the sustained analogue to a pulse emission: (b) constant aviation emissions on the 2000 level. Further we consider two aviation emission types related to real world scenarios: (c) aviation scenarios representing actual emission development before 2005 (IEA, 2006) and follow then either the low $B1_{acare}$ or the high growth A1 scenario (Owen et al., 2010) up to the year 2100 with subsequent stabilisation. Our framework assumes, for the year 2000, a CO_2 concentration of 369 ppmv. The background concentration is held constant or follows either an ambitious stabilisation pathway in line with the 2 °C target (RCP2.6, Van Vuuren et al. (2011)) or the high growth concentration pathway RCP6.0 (Masui et al., 2011), see also Fig. A.1, p. 118.

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3.3 Results

3.3.1 Policy objective

Physical cost–benefit approach

For the generic trade-off situation, the contrail pulse metrics GWP, MGTP and GTP_p for the base and the contrail mitigation case are displayed as function of time horizon H (Fig.3.2a). With increasing time horizons H, all metric values show a declining tendency, and thus indicate the ever smaller relevance of a contrail forcing. In the contrail mitigation case the metric values are about half that of the base case. This constant ratio results from the assumed time-invariant contrail reduction factor and fuel penalty in the contrail migration case.

The ratios R (*cms* vs. *base*) are presented in Fig.3.2b, including the determined turning points. When using physical cost- benefit metrics, smaller evaluation horizons favour the contrail mitigation case, larger horizons the base case. The corresponding turning points, where both cases are equally favourable ($R = 1$), amount to 34 a, 89 a, and 119 a when using GTP_p, $MGTP_p$, and GWP, respectively. The ΔT-based end point metric GTP_p yields the smallest turning point. The turning point is more than doubled if the corresponding average metric (MGTP) is used, and delayed by another 30 a (33 %) if instead of ΔT, RF is taken as proxy for climate change (GWP). For an evaluation horizon H_{cba} of more than 120 a, the considered standard pulse metrics invariably favour the base case. Analogously, the contrail mitigation case is preferred for an evaluation horizon smaller than 34 a. In between, the underlying proxy for the climate impact (RF,

ΔT) and the weighting function (average, end point) control the decision on the more climate-friendly case (Fig.3.2c).

Physical cost-effective approach

In the physical cost-effective framework we determine the contrail pulse metrics $\mathrm{GTP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$, $\mathrm{MGTP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$ and $\mathrm{GWP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$ with t being the distance D^{tar} to a climate target in 2100 (Fig.3.3a). Again, the contrail mitigation case metrics are about half as large as the corresponding base case metrics. Physical cost-effective contrail metrics show a common trend: For a large distance to the target, small values are assigned to the short-lived contrail effect. Considering a short distance, the metric values grow; the contrail-induced climate impact swiftly becomes more important than the CO_2 effect. Ratios and corresponding turning points are calculated (Fig.3.3b). If the evaluation is based on the standard end point metric $\mathrm{GTP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$ the turning point is 50 a before the target is reached, in our case in 2050. If integrated RF or ΔT are taken as proxies ($\mathrm{GWP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$, $\mathrm{MGTP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$, respectively), a lowering of the flight levels results in a smaller climate impact than the base case right on from the year 2000, i. e. $D^{tar} \geq 100$ a (Fig.3.3c).

3.3.2 Sensitivity to background conditions and aviation emission type

We now vary atmospheric background conditions (Section 3.2.5) and derive corresponding turning points for GWP, MGTP and GTP_p (Fig. 3.4). Assuming an

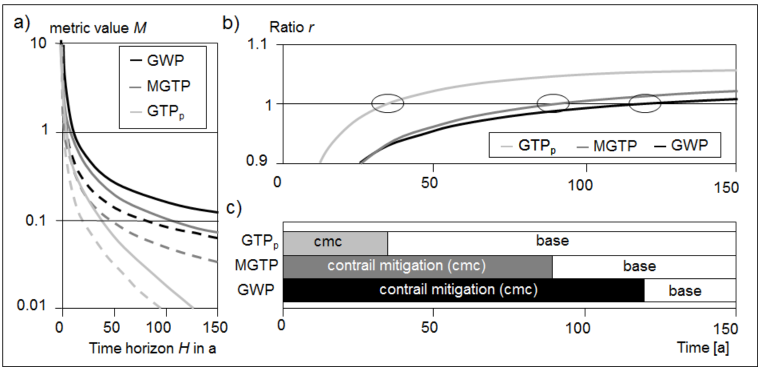

Figure 3.2: *(a) Physical cost-benefit contrail* GTP_p*, MGTP (red) and GWP for the base case (solid lines) and the contrail mitigation case (dashed lines) as a function of the time horizon* *(b) ratio R calculated from contrail metrics of (a) as a function of time horizon H. Turning points are marked by circles. (c) Schematic display of the preferred option according to Fig. 3.1*

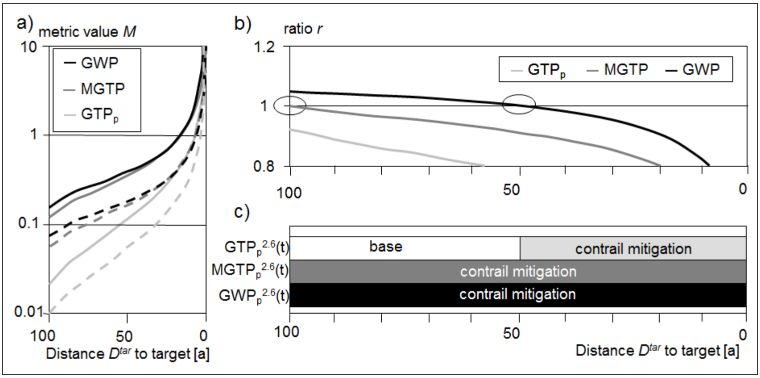

Figure 3.3: *Physical cost-effective contrail* $\mathrm{GTP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$, $\mathrm{MGTP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$ *and* $\mathrm{GWP}_\mathrm{p}^{\mathrm{RCP2.6}}(\mathrm{t})$ *for the base case (solid lines) and the contrail mitigation case (dashed lines) as a function of the distance* D^{tar} *to a target in 2100. (b) ratio R calculated from metrics in (a) as a function of* D^{tar}*. Turning points are marked by circles. (c) Schematic display of the preferred option as a function of* D^{tar}*.*

ambitious stabilisation pathway (RCP2.6), the contrail mitigation case remains preferential for slightly larger evaluation horizons (+3 a ($T_{TP}[\mathrm{GTP}_\mathrm{p}^{\mathrm{RCP2.6}}]$), +12 a ($T_{TP}[\mathrm{MGTP}_\mathrm{p}^{\mathrm{RCP2.6}}]$) and +24 a ($T_{TP}[\mathrm{GWP}_\mathrm{p}^{\mathrm{RCP2.6}}]$)) compared to a constant atmospheric background.

When assuming strongly increasing atmospheric concentration levels (RCP6.0), the turning point increases even stronger, by around 20 % (89 – 109 a) for MGTP_p and it almost doubles from 118 a to 220 a for GWP. Hence, in case of average metrics, the selected proxy for climate impacts (ΔT or RF) strongly affects the timing of the turning point.

A pulse temperature-based end point metric is rather insensitive to a variation of background conditions ($T_{TP}[\mathrm{GTP}_\mathrm{p}^{\mathrm{const}}] = 34$ a; $T_{TP}[\mathrm{GTP}_\mathrm{p}^{\mathrm{RCP6.0}}] = 37$ a). Generally, metric values which take into account increasing atmospheric CO_2concentrations levels turn out to be larger, as the CO_2 related denominator decreases due to spectral radiative saturation effects. This, in turn, results in larger turning points.

Second, we vary the aviation emissions type from pulse to sustained and to emission scenarios, respectively (Section 3.2.5). In the case of pulse emissions the short-lived climate response decays rapidly. Sustained emissions, however, cause constant (RF as proxy) or slightly increasing short- lived effects (ΔT) while the corresponding long-lived CO_2 effect builds up only gradually. Hence, we obtain a significantly enlarged range of turning points for sustained emissions ($T_{TP}[\mathrm{GTP}_\mathrm{s}^{\mathrm{const}}]$=132 a, $T_{TP}[\mathrm{MGTP}_\mathrm{s}^{\mathrm{const}}]$=233 a and $T_{TP}[\mathrm{GWP}_\mathrm{s}^{\mathrm{const}}]$=457 a (Fig. 3.4). The consideration of sustained instead of pulse emissions (constant atmospheric conditions) approximately triples (MGTP) respectively quadruples (GWP, GTP_p) the turning point, i. e. the contrail mitigation case remains the preferred option for much larger time horizons. If instead of sustained emission the aviation stabilisation scenario B1acare is taken as basis, only a small deviation for the turning point show up: –1 a, +7 a, and +6 a for $GTP^{const}_{B1acare}$, $MGTP^{const}_{B1acare}$, and $GWP^{const}_{B1acare}$, respectively. Slightly larger changes are found if a high growth scenario until 2100 with subsequent stabilisation of the emission level is considered: +44 a, +38 a, and –1 a for GTP^{const}_{A1}, $MGTP^{const}_{A1}$, and GWP^{const}_{A1}, respectively.

Third, we consider the combined effect of sustained aviation emissions and increasing CO_2 concentration pathways. For the ambitious CO_2 concentration scenario (RCP2.6), in case of pulse emissions, CO_2 saturation effects result in comparably minor deviations of the turning points (–5 a $T_{TP}[\,GWP^{RCP2.6}_{s}\,]$; +17 a $T_{TP}[\,GTP^{RCP2.6}_{s}\,]$; +28 a $T_{TP}[\,MGTP^{RCP2.6}_{s}\,]$). A remarkably different perspective on the trade-off situation, however, is obtained for a high concentration pathway (RCP6.0). CO_2 saturation effects are here much more pronounced if sustained emissions instead of a pulse emission are considered, resulting in turning points which are about 3 times larger that those related to sustained emission and constant atmospheric conditions: $T_{TP}[\,MGTP^{RCP6.0}_{s}\,] = 635$ a; $T_{TP}[\,GWP^{RCP6.0}_{s}\,] = 1459$ a; $T_{TP}[\,GTP^{RCP6.0}_{s}\,] = 323$ a and 7 – 12 times larger than those of the corresponding standard metrics. Hence for all these combinations the contrail mitigation case becomes more preferable if saturation effects act to dampen the long-lived CO_2 effect.

3.3.3 Parametric uncertainty

Finally, we evaluate the sensitivity of the turning point to parametric uncertainty (Section 3.2.4) by means of standard physical cost-benefit metrics. Potentially, contrail cirrus has the most prominent impact according to our sensitivity analysis. Turning points substantially grow in the assumed cirrus mitigation case substantially (Fig. 3.4). If the end point metric $GTP_p(t)$ is applied it is doubled to 70 a. In case of average metrics the turning point is enlarged by factors of 3 – 6 (T_{TP}[MGTP]) = 332 a, T_{TP}[GWP] = 707 a). These results illustrate that when using average-based metric, the preferred climate mitigation option for any time horizon below 332 a is the contrail mitigation case.

Second, when varying the contrail efficacy r_{con} from 0.59 to 0.3 and 1 the turning points about halve or double ($T_{TP}\,(r_{con})$ [GWP] = [49 a; 274 a], $T_{TP}\,(r_{con})$ [MGTP] = [44 a; 159 a], $T_{TP}\,(r_{con})\,[\,GTP_p\,]$ = [20 a; 50 a]). This parametric uncertainty increases substantially the spread of turning points from different metrics.

Third, we vary climate response time τ. This sensitivity occurs only if temperature change is chosen as proxy for climate change (GTPp, MGTP). A variation of t in the range of 10 – 50 a (Section 3.2.4) affects the turning points only slightly: $T_{TP}(\tau)[\,GTP_p\,]$ = [19 a; 38 a]; $T_{TP}(\tau)$[MGTP] = [64 a; 94 a]. In absolute terms the τ-sensitivity is significantly less than other parametric uncertainties presented above. Finally, the choice of climate sensitivity while influencing the metric val-

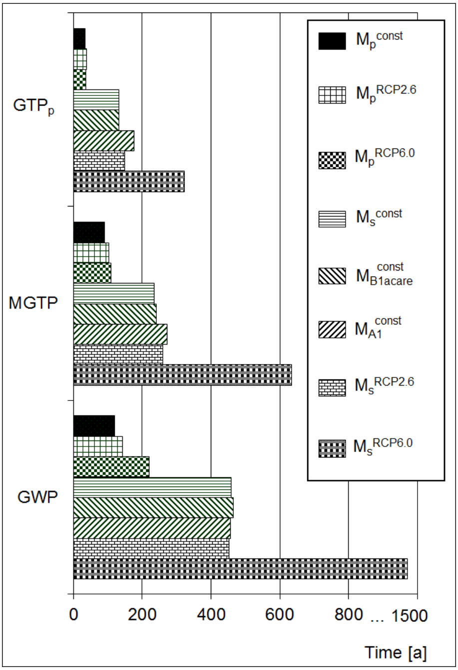

Figure 3.4: *Turning point based on standard contrail GWP,* GTP_p *and MGTP, determined for different assumptions on background conditions (*$M_p^{RCP2.6}$*,* $M_p^{RCP6.0}$*), aviation emission types (*M_s^{const}*,* $M_{B1acare}^{const}$*,* M_{A1}^{const}*) and combined effects from sustained emissions in face of a variation in background conditions (*$M_s^{RCP2.6}$*,* $M_s^{RCP6.0}$*)*

ues does not affect the turning point; variations cancel as they affect short- and long-lived effects in equal measure.

3.4 Discussion

3.4.1 The turning point concept

We have established the concept of the turning point to determine the preferable climate mitigation option. The turning point depends on normative decisions based on policy and common sense consideration. Additionally, it is to some extent uncertain due to uncertainties in atmospheric science. In the cost-benefit policy framing, the normative decision on selecting an evaluation horizon H_{cba} represents an essential step for identifying the more climate-friendly case: Small horizons (e. g. $H_{cba} = 50\,a$) tend to favour the contrail mitigation case while large horizons (e. g. $H_{cba} = 500\,a$) promote the base case. For an evaluation horizon

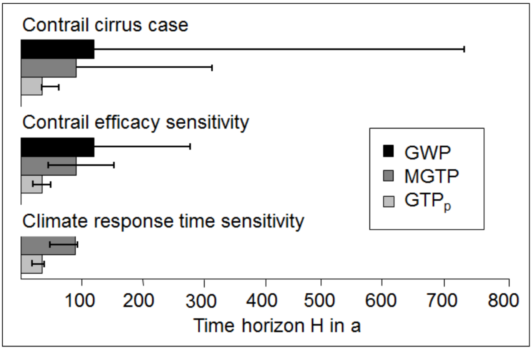

Figure 3.5: *Turning points calculated from contrail* GTP_p*, MGTP and GWP as a function of time horizon H with uncertainty ranges referring to the cirrus case, contrail efficacy* r_{con} *and climate response time* τ

in between, the recommended mitigation strategy critically depends on metric choices (weighting function, proxy for climate impact) and underlying assumptions on future developments (background, aviation emission type) (Table 3.1).

The turning point concept reveals a potentially misleading feature when applying metrics. If the evaluation horizon H_{cba} lies close to the turning point, even a small variation in H_{cba} can induce a switch to an opposite policy recommendation. Similarly, the policy recommendation may be highly sensitive to the selected metric if corresponding turning points are close to each other. Evaluation by using turning points allows identifying such critical value range for H_{cba} and metric types.

In the following we focus on the sensitivity of a policy recommendation on individual policy decisions and scientific uncertainty, quantified by applying the turning point concept.

3.4.2 Metric choice and assumptions on future development (CBA)

Our analysis shows that end point metrics (GTP_p) result in turning points that are smaller by approximately 65 % (45 %) in case of pulse (sustained) emissions than corresponding turning points of average metrics (MGTP) (Fig. 3.5). They generally promote the base case for noticeably smaller evaluation horizons than average metrics (Table 3.1, e. g. H_{cba} of 50 and 100 a for pulse, 200 a for sustained emissions). End point metrics ignore impacts between emission release and the considered end point, which put less emphasis on short- lived effects.

A *RF*-based metric abandons to include the thermal inertia of the climate system (Fuglestvedt et al., 2003). Using *RF* as proxy (GWP) results in systematically larger turning point than the corresponding temperature-based metric

		Evaluation horizon H_{cba} in *a*											
		50			100			200			500		
		Metric choice											
	Emission type, *background*	GWP	GTP	MGTP	GWP	GTP	MGTP	GWP	GTP	MGTP	GWP	GTP	MGTP
Standard	pulse, *const*	⇓	○	⇓	⇓	○	○	○	○	○	○	○	○
Background	pulse, *RCP2.6*	⇓	○	⇓	⇓	○	⇓	○	○	○	○	○	○
	pulse, *RCP6.0*	⇓	○	⇓	⇓	○	⇓	⇓	○	○	○	○	○
Aviation emission type	sustain, *const*	⇓	⇓	⇓	⇓	⇓	⇓	⇓	○	⇓	○	○	○
	B1acare, *const*	⇓	⇓	⇓	⇓	⇓	⇓	⇓	○	⇓	○	○	○
	A1, const	⇓	⇓	⇓	⇓	⇓	⇓	⇓	○	⇓	○	○	○
Background and	sustain, *RCP2.6*	⇓	⇓	⇓	⇓	⇓	⇓	⇓	○	⇓	○	○	○
aviation emission type	sustain, *RCP6.0*	⇓	⇓	⇓	⇓	⇓	⇓	⇓	⇓	⇓	⇓	○	⇓

Table 3.1: *Policy recommendation for the contrail mitigation case (⇓) or the base case (○) for different evaluation horizons H_{cba}, metric choices, assumed atmospheric concentration pathways and aviation emission types (CBA)*

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(MGTP), meaning a stronger weighting of short-lived effects. This bias towards the contrail mitigation case is noticeable already in case of pulse emission and constant atmospheric conditions (T_{TP}[GWP] = 119 a, T_{TP}[MGTP] = 89 a, Fig. 3.5). For example, it induces a switch in policy recommendation for the common evaluation horizon H_{cba} of 100 a. The turning points diverge even more if future atmospheric CO_2 concentrations increase (e. g. $T_{TP}[\,GWP_p^{RCP6.0}\,] = 220$ a; $T_{TP}[\,MGTP_p^{RCP6.0}\,] = 109$ a) and becomes particularly pronounced if sustained or scenario emissions are considered.

Assuming an ambitious climate stabilisation pathway (RCP2.6) instead of constant atmospheric conditions causes small turning point shifts and leaves the policy recommendations robust. Nevertheless the misleading feature mentioned above shows up in this case: $T_{TP}[\,MGTP^{const}\,]$ =89 a and $T_{TP}[\,MGTP^{RCP2.6}$] =101 a are close to each other; an evaluation horizon in the range of 90 – 100 a results in opposite policy recommendation using these two metrics. Considering a high growth scenario (RCP6.0) leads to changes in policy recommendations more frequently.

Finally, the policy recommendation is strongly sensitive towards the choice of the aviation emission type: for instance, the large turning point shifts from pulse to sustained emissions explain the switch in policy recommendation for a wide range of evaluation horizons (Table 3.1). Which aviation emission type is most appropriate for evaluation is closely linked to the actual policy question. For instance, when comparing the climate impact caused by different aircraft designs it is reasonable to consider sustained emissions over a defined time horizon, equivalent to the aircraft's in-service time (Schwartz Dallara et al., 2011). If, however, the policy question does not suggest an obvious decision on the aviation emission type, more detailed normative considerations on merits and shortcomings are required: A pulse consideration creates formal independence from any assumption on future aviation developments. Choosing sustained or scenario emissions include precisely the latter, but as a consequence limitations arise from scenario-inherent uncertainties. We regard, however, reasonable assumptions on a future scenario as a prerequisite for developing a common-sense mitigation strategy involving ongoing short- and long-lived effects as a complete cease of aviation is unrealistic.

The fact that GWP (pulse emission, *RF*-based) and GTP_s (sustained emission, ΔT-based) lead to the same policy recommendation was earlier observed by Shine et al. (2007). Our analysis shows that opposite trends towards the one or the other case caused by individual choices such as aviation emission type and proxy for climate impacts might level out, essentially coincidental.

3.4.3 Shortcoming of defining a rigid policy target

The way, in which a policy target is pursued (*CBA* vs. *CEA*), opens two different views on one and the same trade-off situation: Under a cost-benefit approach the preferred option depends on a normative decision (evaluation horizon H_{cba}).

In contrast, using a physical cost-effective metric leads always to a point in time (viz., the turning point, the distance D_{tar}^{TP} at which the mitigation case becomes the preferred option, independent from metric choices (Fig. 3.3). While physical cost-effective metrics have already been discussed in literature (Shine et al., 2005, 2007; Shine, 2009; Azar and Johansson, 2011) our results systematically highlights the practical consequences of applying them for a specific trade-off problem.

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The physical cost-effective approach is methodologically critical through its fixed target year. All considered metrics ignore the long-term climate effects beyond the chosen time frame parameter (time horizon H or distance D^{tar}). However, only in the physical cost effective framework particularly small time frame parameters emerge by construction (e. g. D^{tar} < 20a) when the target is approached, leading to an unacceptably pronounced bias towards short-lived effects. Further, the fixed target year which determines the distance D^{tar}, is pivotal for the policy recommendation but actually arbitrary. Sustainable stabilisation requires that the mitigation target is maintained not only at one point in time (e. g. in 2100) but also at any time beyond. In the cost-effective policy framing, physical metrics deliver important insights into structural effects when weighting short- and long-lived effects. However, they fake a scientific-based policy recommendation when actually a critical normative decision on temporal impact weighting is required.

3.4.4 Scientific uncertainty and common sense decisions

Parametric uncertainties related to contrail efficacy and contrail cirrus have the potential to result in a switch in policy recommendation compared to the standard case for a wide range of evaluation horizons: e. g. the contrail efficacy value finally determines the policy recommendation for evaluation horizons of 50 a, 50 – 100 a, and 50 – 200 a, if GTP_p, MGTP and GWP, respectively, are applied. Analogously, parametric uncertainty related to contrail cirrus might lead to a switch in policy recommendation if evaluation horizons of 50 a (GTP_p), 100 – 200 a (MGTP), and 200 – 500 a (GWP) are chosen (Fig. 3.5). If contrail cirrus RF consolidates around current estimates and if contrail cirrus occurrence proves as sensitive to lowering the flight altitude as line-shaped contrails, any common sense decision (on the evaluation horizon, metric) clearly favours the mitigation case option. In contrast to the structural metric sensitivities discussed above, parametric uncertainties will gradually diminish with expected progress in atmospheric science.

We are fully aware that our systematic evaluation contains some metric values that are at odd with common sense, e. g. those assuming constant aviation emissions over the next 500 years. The danger of inflicting intrinsic inconsistencies by choice of a certain metric emphasises that normative decisions always require additional considerations. These are based on common sense and not a direct consequence of results from atmospheric climate science.

3.5 Conclusion and outlook

We demonstrated that, for evaluating a trade-off between short- and long-lived climate effects, the first and fundamental steps are to take normative decisions on optimisation strategy (policy approach), evaluation horizon and assumptions on future aviation developments and background conditions. These policy decisions constrain the range of appropriate metric choices for evaluation and may have a direct influence on favouring either the base case (by choosing, e. g. large evaluation horizons or pulse emissions) or the contrail mitigation case (small evaluation horizons or sustained emissions). Evaluating the options by means of turning points provide guidance on the recommended course of action. Our most important findings are:

- Physical cost-effective climate metrics ($GTP_p(t)$, $MGTP_p(t)$, $GWP_p(t)$) are methodologically problematic for providing final policy conclusions. When using physical metrics, we recommend remaining in the cost benefit policy framing.
- Within the cost benefit policy framing, we favour to account for all climate effects within the evaluation horizon as being most representative and best justified from an ethical point of view. This involves the preference of an average weighting function to weigh short and long-lived effects.
- Global mean temperature change is the more reasonable physical proxy for climate impacts as it reliably reflects the response characteristic of the earth climate system. However, for reasons of simplicity, taking integrated *RF* as the proxy remains a viable alternative. The resulting bias towards short-lived gases remain acceptable, as long as an aviation pulse emission is considered and expected future atmospheric conditions remain sufficiently close to present day conditions.
- In a similar sense, the assumption of constant atmospheric conditions for physical cost-benefit metric calculation forms a viable simplification option, if there are reasons to expect the implementation of ambitious climate policies. If climate policy fails, the same assumption, however, would result in a bias towards favouring mitigation of short-lived effects, non-negligibly pronounced in case of sustained and scenario emissions.
- The choice of the aviation emission type (pulse, sustain, scenario) may prove crucial for the evaluation outcome. Our evaluation framework illustrates the consequences of the respective choice but the choice itself remains related to the underlying policy question and is of normative nature.
- If the assumptions for our sensitivity test involving contrail cirrus are supported by future atmospheric research, the mitigation case clearly becomes the favoured option.

For an evaluation horizon H_{cba} of 100 a (as in the Kyoto Protocol), the metric types, which we consider as most suitable, tend to promote the contrail mitigation case. Such mitigation strategy has not yet been performed in practice.

Apart from considerations including the larger contrail cirrus effect and the climate impact reduction with respect to NO_x, several arguments would support this strategy: Generally, the mitigation of a large short-lived at the expense of a small long-lived effect is in line with the normative perception that limiting the rate of change is of equal importance as long-term optimisation. Further, in aviation, in contrast to other sectors, it is more difficult to replace the current fuel supply by a carbon-free alternative. The long-term CO_2 mitigation potential is limited. Likewise, the unusually large fraction of aviation-induced short-lived non-CO_2 effects results in a substantial, aviation specific short-term climate impact mitigation potential. Such different reduction potential levels in different sectors could advocate of diverging optimisation strategies: emphasising short-term reduction in aviation and accepting a slightly increased long-term effect in future times when other sectors have already implemented a low carbon energy supply.

Finally, we note some additional arguments suggesting a careful preparation of a contrail mitigation strategy: as a general lowering of flight levels represents a simplified approach and forms a fundamental intervention into the current air traffic system, it could be more convincing to initiate some technological change for the more efficient, climate-optimised flight trajectories. The fuel penalty, crucial for the evaluation outcome, has been taken here as invariant. It could, however, substantially be reduced by new aircraft design and flight performance such as cruise speed reduction, (e. g. Egelhofer, 2009; Filippone, 2010). Providing incentives for the pre-development of aircrafts which cruise with lower or no fuel penalty in lower flight altitudes is a promising first step. Further, a moderately delayed implementation of the mitigation strategy would provide the opportunity to combine expected progress in air traffic management system including operational aspects, weather forecast systems, and scientific understanding of the contrail climate impact (Frömming et al., 2012). An advanced future management system could facilitate a selective mitigation of only those linear contrail and contrail cirrus which are expected to induce a substantially positive RF during their lifetime (Mannstein et al., 2005). In one or two decades, when the need for short-term reduction is more pronounced as the rate of climate change becomes more remarkable a more efficient flight route management system could finally be implemented. Then, an improved scientific understanding also of regional climate change can be expected and will hopefully be accounted for in the management of flight trajectories.

3.6 Acknowledgement

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Chapter 4

CO_2 equivalences for short-lived climate forcers

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4.1 Introduction

Global warming can be curbed not only by mitigating emissions of long-lived greenhouse gases such as carbon dioxide (CO_2) or methane (CH_4), but also by reducing levels of short-lived climate forcers (SLCF) (Jackson, 2009; Penner et al., 2010). Hence, including SLCF in cost-efficient mitigation strategies becomes increasingly relevant. SLCF are agents with atmospheric residence times of less than one year that substantially contribute to global mean radiative forcing (RF), either resulting from precursor-induced changes in concentration of radiatively active gases (e. g. nitrogen oxides NO_x–induced ozone) and aerosols (such as warming black carbon or cooling sulphate) or through changes in cloud cover and radiative properties of clouds (e. g. contrails or ship tracks). The short atmospheric lifetimes of these agents and their effects results in a spatially inhomogeneous atmospheric distribution, which is concentrated around their source. The emission and precursor-to-impact relationships exhibit regional differences (e. g. Berntsen et al., 2006; Rap et al., 2010; Bond et al., 2011; Frömming et al., 2012): The occurrence of SLCF and the consequential RF (RF_{SLCF} in the following) strongly depend on (i) the location of the (precursor) emission, (ii) the prevailing atmospheric conditions and (iii) the actual insulation. In contrast, long-lived climate forcers (LLCF) are independent of emission time and location. This results in quasi-homogeneous changes in concentrations which accumulate in the atmosphere and remain for decades or centuries.

When designing cost-efficient mitigation strategies (e. g. emission pricing, emissions trading schemes, life-cycle assessment, and offsetting schemes), there is a need to compare the impact of different atmospheric forcers. This is usually done by determining the CO_2 equivalence in terms of an emission-based global mean metric (Fuglestvedt et al., 2010), i. e., by determining the amount of CO_2 that has the equivalent impact as a unit (e. g. 1 kg) of emission of another agent. The established metric concepts, such as the global warming potential (GWP) (IPCC, 1990), the mean global temperature potential (MGTP) (Gillett and Matthews, 2010; Marais et al., 2008) and the economic cost-benefit metric global damage potential (GDP) (Hammitt et al., 1996), were originally designed for comparing different LLCF. A particular challenge arises when SLCF with substantially different atmospheric properties to LLCF are to be included in the evaluation.

Designing a metric for SLCF requires a series of policy decisions and value judgement. In particular, the selection and parametrisation of a metric type involves the choice of a proxy for climate impacts along the chain of impacts, and the weighting of impacts along the temporal axis (e. g., Forster et al. 2007; Tanaka et al. 2010; Deuber et al. 2013a or Chapter 2). Early discussions on metrics for SLCF were limited to physical metrics, particularly with regards to the aviation sector (e. g., Rypdal et al. 2005; Shine et al. 2005, 2007; Deuber et al. 2013b or Chapter 3) and black carbon (e. g. Boucher and Reddy, 2008; Bond et al., 2011). This has recently changed with a growing scientific interest in including the economic perspective (Plattner et al., 2009; Shine, 2009). Economic-based metrics account for the potentially non-linear relationship between physical impact parameters and economic damages. Several recent studies discuss the implication of such metrics for aviation emissions (Marais et al., 2008; Dorbian et al., 2011; Azar and Johansson, 2011; Johansson, 2012) and for methane (Boucher, 2012). They offer key insights into the discussion on economic CO_2 equivalences for SLCF.

Our objective is to determine CO_2 equivalences for SLCF using metric-based approaches. We introduce a generic approach to calculate SLCF metrics which is applicable irrespective of the exact nature of the SLCF agent or the corresponding activity. We highlight the implications of the common characteristics of SLCF (atmospheric lifetime of less than one year, no long-term accumulation) for the calculation of global mean CO_2 equivalences. Such an approach has not previously been reported in the literature. The sensitivity of economic-based metrics to the choice of input variables has so far only been evaluated through specific examples and with a limited range of parameters (e.g. Dorbian et al., 2011). We go further and generalise these results by performing a multi-dimensional sensitivity study on our generic economic-based CO_2 equivalences. This aids understanding the merits and limits of economic considerations in metric design and allows evaluating sensitivities from metric choice in the context of normative value judgements and SLCF-specific physical uncertainties.

Specifically,

(1) we explore the sensitivity structure of the generic CO_2 equivalences for SLCF towards its input variables and over time, based on the economic metric GDP.

(2) we illustrate how GDP-based CO_2 equivalences compare to those based on physical metrics. The analysis reveals how the CO_2 equivalence for SLCF is affected by

- the degree of convexity of the economic damage function,
- the assumption on future concentrations pathways,
- the normative choice of discount rate,
- physical characteristics of the climate system,
- the proxy for climate impacts and aggregation of emissions along the temporal axis, and
- the point in time of emission release.

(3) we demonstrate the usefulness of the generic approach by applying it to the aviation-induced contrails.

4.2 Methodology

To determine metric-based CO_2 equivalences for SLCF, we transfer and adapt the concept of emission-based global mean climate metrics to the features of indirect SLCF. For conceptual clarity we distinguish between different types of factors for calculating CO_2 equivalences and show how they are interrelated.

4.2.1 Metric-based CO_2 equivalences for SLCF

We apply emission-based global mean climate metrics in the form of CO_2 equivalence factors in order to compare the climate effect of emissions of different greenhouse gases. The CO_2 *equivalence factor* is defined as the ratio of absolute metric values: $EQ_M = AM_i/AM_{CO_2}$ (e. g. Forster et al., 2007), where AM_i is the absolute metric value for a unit emission (e. g., 1 kg) of an agent i and M is the chosen metric. Hence, the CO_2 equivalence of a non-CO_2 emission is calculated by multiplying the respective non-CO_2 emission by EQ_M.

There is a general form that applies to all metric concepts, according to which the absolute metric value AM_i can be expressed as the temporally aggregated weighted impact I induced by a unit pulse perturbation of the agent or effect i (Forster et al., 2007):

$$AM_i = \int_{t=t_0}^{\infty} \left[(I(\Delta C_{ref+i}(t) - I(\Delta C_{ref})(t)) \cdot W(t) dt \right] . \tag{4.1}$$

$I(\Delta C_{ref+i})(t)$ is defined as the impact I of a change in climate ΔCC (such as concentration change, global temperature change, or precipitation change) at time t from a unit pulse perturbation i under emission pathway *ref*. *W(t)* describes the weighting of impacts over time, e. g. constant weighting over a distinct time horizon or exponentially decreasing weighting such as economic discounting.

When extending the concept of emission-based metrics to SLCF and indirect precursor emissions, two aspects become critical:

- Differences in atmospheric properties of SLCF and CO_2, and the differences in induced spatial climate change pattern complicate a direct comparison by means of one impact proxy I.
- Due to spatial and temporal heterogeneity, there is only an approximate relationship between emissions, the emergence of indirect SLCF and the climate change induced. For some indirect SLCF (e. g. contrails), emission release has limited use as a proxy for climate impacts.

Due to these limitations, SLCF metrics will always be subject to a high level of uncertainty; yet CO_2 equivalences for SLCF are important for practical and policy applications, as discussed in the introduction. A pragmatic approach to dealing with these limitations is to make use of an assumed linear relationship between the annual sum of SLCF and the induced global mean RF (including its temporal evolution) in any given year and to consider RF as an impact proxy I for comparing the climate effects of SLCFs and CO_2. Global mean RF is scientifically well understood, and RF and its effect on the climate system along the chain of impacts are commonly considered in metric design. As a first approximation, these global mean impact proxies can be also used for SLCF, if one accepts that information on regional scale is lost.

We introduce three alternative types of global mean metric-based CO_2 equivalence factors. These can be related to different metric concepts and used to calculate CO_2 equivalences from reference quantities. Depending on the reference quantity to which climate effects of the SLCF are normalised, we distinguish between:

- the forcing-based factor EQ_M describing CO_2 equivalences per unit of average global mean annually integrated RF induced by SLCF [kg_{CO2e} (W m^{-2} a)$^{-1}$]. This can also be viewed as CO_2 equivalences per year per unit of average global annual mean RF [(kg_{CO2e} a^{-1}) (mW m^{-2})$^{-1}$];

- the activity-based factor EQ_M^A reflecting CO_2 equivalence per activity unit (e.g. emissions of black carbon or NOx, flight distance) [kg_{CO_2e}/ kg_{SLCF}, kg_{CO_2e} / km_{flight}], and
- the fossil-fuel based factor EQ_M^A for combustion-related SLCF providing CO_2 equivalences per unit of CO_2 emissions caused by the same fossil-fuel based combustion process [kg_{CO_2e}/kg_{CO_2}].

For the evaluation of a specific emission situation, all types of CO_2 equivalent factors should be corrected by the agent-specific efficacy E_{SLCF}. Introducing the efficacy, the global temperature response per unit non-CO_2 forcing relative to the response produced by a CO_2 forcing, allows to compare a forcing from an extremely inhomogeneous perturbation (RF_{SLCF}) to that induced by a homogeneous CO_2 forcing (e.g. Joshi et al., 2003; Hansen et al., 2005). The forcing-based equivalence factor with a standard efficacy $E_{SLCF} = 1$ depends solely on the climate forcing induced by the SLCF, but not on properties that are specific to the SLCF source. This allows us to calculate numerical CO_2 equivalence factors for a wide array of parameter values, which are independent of the SLCF agent and situation. Due to its generic nature, we use this factor for much of the numerical assessment in Section 4.3.

The activity-based factor is calculated in the same way as metrics for long-lived greenhouse gases. The fossil-fuel based factor is commonly used in the context of aviation-induced contrails (Gierens et al., 1999; Forster et al., 2006; Fuglestvedt et al., 2010), because many aviation emission inventories do not provide spatially resolved flight distances. These two factors can be derived from the generic one by applying agent and year specific scaling factors that describe the efficacy-corrected global mean RF_{SLCF} either per unit emission [$(mW\ m^{-2}\ a)/kg_{EM}$] (in case of aviation per unit flight distance [$(mW\ m^{-2}\ a)/ km$]) or per kg combustion-related CO_2 [$(mW\ m^{-2}\ a)/ kg_{CO_2}$].

4.2.2 Global mean metric approaches

Global Damage Potential

The Global Damage Potential (GDP) calculates the metric value as the ratio of the net present values of the economic damage from SLCF ($AGDP_{SLCF}$) relative to that from CO_2 ($AGDP_{CO_2}$). It accounts for the entire chain of impacts along a specific atmospheric concentration pathway and uses a discounting weighting function with the discount rate r (Appendix Eq. A.2, page 120). The GDP can be derived from first economic principles that result in an economically optimal allocation of the mitigation burden across forcing agents (Eckhaus, 1992; Hammitt et al., 1996). Due to its welfare-economic optimality, it can serve as benchmark against which other metric approaches can be compared (Deuber et al. 2013a or Chapter 2, respectively). For the purposes of studying the GDP-based CO_2 equivalences, we assume a convex damage function D with time t dependent global mean temperature change $\Delta T(t)$ as an impact parameter in the form of

$D = \alpha \cdot \Delta T^n$ with n being the damage function exponent. An exponent $n > 1$ results in a convex damage function, in line with the common finding in climate economics that the damage grows more rapidly with increasing temperature change (e. g., Stern, 2007; Nordhaus and Boyer, 2000; Hammitt et al., 1996). This framework provides the CO_2 equivalence factor for any single SLCF:

$$EQ_{GDP} = \frac{AGDP_{SLCF}}{AGDP_{CO_2}} = \frac{\int\limits_{t=t_0}^{\infty} (\Delta T_{ref+SLCF}(t))^n - \Delta T_{ref}(t)^n \cdot e^{-rt} dt}{\int\limits_{t=t_0}^{\infty} (\Delta T_{ref+EM_{CO_2}}(t))^n - \Delta T_{ref}(t)^n \cdot e^{-rt} dt} \quad (4.2)$$

Note that the damage co-efficient γ is cancelled out in this equation, since it applies to both the SLCF and CO_2 effect.

Physical metrics

For comparing physical and economic metric based CO_2 equivalences we consider the GWP and MGTP metrics. These are both based on the assumption of a linear relationship between the physical impact parameter and the economic damage ($n = 1$). They refer to the ratio of changes in physical impact parameters, assuming constant atmospheric conditions at the time of emission release. The impact parameters are either integrated RF (GWP, Eq. A.5, page 120) or global mean temperature change ΔT (MGTP, Eq. A.6, page 120). By convention, the metrics consider the climate impact I over a finite time horizon H (unit step function, Eq. A.7 and Eq. 2.2, page 120 and 22, respectively): GWP(H), MGTP(H). Additionally, we consider metric versions incorporating a discounting function: GWP_d(r), $MGTP_d$(r).

4.2.3 Modelling of physical climate change

We compute ΔT_{CO_2} and ΔT_{SLCF} from CO_2 emissions and RF_{SLCF} respectively, using the linear response model LinClim (Lim and Lee (2006) based on Hasselmann et al. (1997), and Sausen and Schumann (2000)). LinClim reproduces the global mean transient behaviour of the comprehensive atmosphere-ocean model ECHAM4/OPYC3 (Roeckner et al., 1999). It assumes that the climate response of SLCF is independent from changes in background atmospheric CO_2 concentration.

As mentioned above we concentrate on contrails as SLCF. Contrails are line-shaped ice clouds that form behind an aircraft when hot and moist exhaust gases mix with cold and sufficiently humid ambient air and saturation with respect to liquid water is reached (Schumann, 2005, e. g.). Contrails may persist for hours and transform to contrail cirrus (Burkhardt and Kärcher, 2011). For practical applications we consider the global aviation emissions in the year 2005 as pulse emissions which result from a global fuel consumption of 232.4 Tg (IEA, 2009; Lee et al., 2010) and approximately 40.7 10^9 flight-km (Lee et al., 2010, Table 3). The aviation-induced RF_{CO_2} of the 2005 emission pulse is calculated as 1.33 mW m^{-2}. RF_{con} amounts to 11.8 mW m^{-2}, and RF_{cirrus} to 33 mW m^{-2}, the latter with an uncertainty range of 11 – 87 mW m^{-2} (Lee et al. (2009); roughly in line with Burkhardt and Kärcher (2011)). Ponater et al. (2005) and Rap et al. (2010) calculated contrail efficacies of $E_{con} = 0.59$ and $E_{con} = 0.31$.

4.2.4 Analysis setting

The sensitivity structure of the economic-based CO_2 equivalences towards their input parameters is presented in the generic form of the forcing-based factor EQ_{GDP} [(Tg_{CO_2e} a^{-1}) (mW m^{-2})$^{-1}$], assuming $E_{SLCF} = 1$. Since understanding the influence of the economic perspective on the CO_2 equivalence is of particular interest in this analysis, we look at a family of CO_2 equivalence factors with different exponents of the damage function n ranging from 1 to 5. We proceed as follows (Appendix, table A.2, page 121): A set of input parameters is defined for the reference case: emission release in year $T_{EM} = 2005$, atmospheric concentrations follow the ambitious stabilisation scenario RCP2.6 (Van Vuuren et al., 2011), time constant of the climate system is set as $\tau = 37.4$ a, and discount rate $r = 2$ % a^{-1}. Subsequently some parameters are varied one by one to reveal sensitivities: time of emission release $T_{EM} = 2050$, 2100; reference concentration pathway RCP6.0 (Masui et al., 2011); time constant $\tau = 10$ a, 50 a; discount rate $r = 4$ % a^{-1}, 0.4 % a^{-1}.

When analysing the effect of the temporal weighting of impacts on the CO_2 equivalences we compare metrics with a finite time horizon to metrics that are subject to discounting. These two weighting functions can be considered similar in effect if the discount rate r is twice the inverse of the time horizon H (Appendix Eq. A.8 page 120). For example, the time horizon H of 100 a corresponds to a discount rate r of 2 % a^{-1}. For numerical reasons, we limit the integration time horizon to $t = 4000$ a where we use exponential discounting, with a negligible effect on our results.

4.3 Results

4.3.1 Economic forcing-based CO_2 equivalent factors

Reference case and convexity of damage function

We start by determining the economic forcing-based CO_2 equivalence factors for SLCF (EQ_{GDP}) for the reference case. EQ_{GDP} depends on the convexity of the damage function (Fig. 4.1a). EQ_{GDP} more than doubles from 8.2 to 19.6 (Tg_{CO_2e} a^{-1}) (mW m^{-2})$^{-1}$ if a linear damage function ($n = 1$) is used instead of one that is highly convex ($n = 5$). A higher convexity leads to higher damage from CO_2 and contrails. However, the relative increase is larger in the case of CO_2, due to its longer atmospheric residence time. Lower convexity places more weight on the years immediately after the pulse emission, thus SLCF are emphasised where n = 1.

Apart from the convexity of the damage curve, the family (with $n = 1$ to 5) is sensitive to other assumptions such as the discount rate, the future atmospheric background or the timing of the emission release (Fig. 4.1a and Appendix, Table A.4, 122). Changes in for a given damage function exponent, e. g., $n = 1$ or 5, (Fig. 4.1b) can be attributed to sensitivities of SLCF or of the reference gas CO_2 to parameter assumptions: For instance, assuming a smaller discount rate of 0.4 % a^{-1}, induces an increase of the CO_2-induced damage ($AGDP_{CO_2}$ that is stronger than the concurrent increase of SLCF-induced damage ($AGDP_{SLCF}$). The corresponding CO_2 equivalence factor therefore becomes smaller (Fig. 4.1a). On the contrary, if reference case emissions are considered to occur in the year 2050 or 2100 in face of a non-linear damage function ($n = 5$), the SLCF-induced damage increases more than the CO_2-induced one, resulting in larger factors than those determined for 2005. If the parameter change affects the SLCF-induced and CO_2-induced damages in a similar manner (e. g., change in climate parameter τ), the factor remains largely unchanged. A detailed analysis of the most important parameter sensitivities is presented in the following sections.

Future atmospheric background

Due to (a) the non-linear relationship (saturation effect) between CO_2 concentration and CO_2-induced RF and (b) the non-linear relationship between temperature and economic damages, depends on the future atmospheric background condition. To illustrate this dependency, we compare the reference case, for which an atmospheric concentration pathway consistent with strong climate policies was considered (RCP2.6), with a concentration pathway representing a world with weak or non-existent climate policy (RCP6.0). EQ_{GDP} is most sensitive to the atmospheric background when the damage function is highly convex: the SLCF-induced damage doubles when compared to the reference case, while the CO_2-induced damage more than quadruples, due to its long atmospheric lifetime (Fig. 4.1b). As a consequence, EQ_{GDP} reduces by more than half. When the damage function is linear, increases only slightly (by 9 %) with increasing background CO_2 concentrations, largely due to the effect of spectral saturation of CO_2 in the RF (decrease in $AGDP_{CO_2}$, Fig. 4.1b). This sensitivity implies that saturation effects from increasing background concentration trends and the effect of the non-linearity of the damage function counteract each other.

Discount rate

The choice of the discount rate reflects a normative weighting of climate effect along the temporal axis: the higher the discount rate, the greater the emphasis on imminent damages. Consequently, a higher discount rate r results in larger CO_2

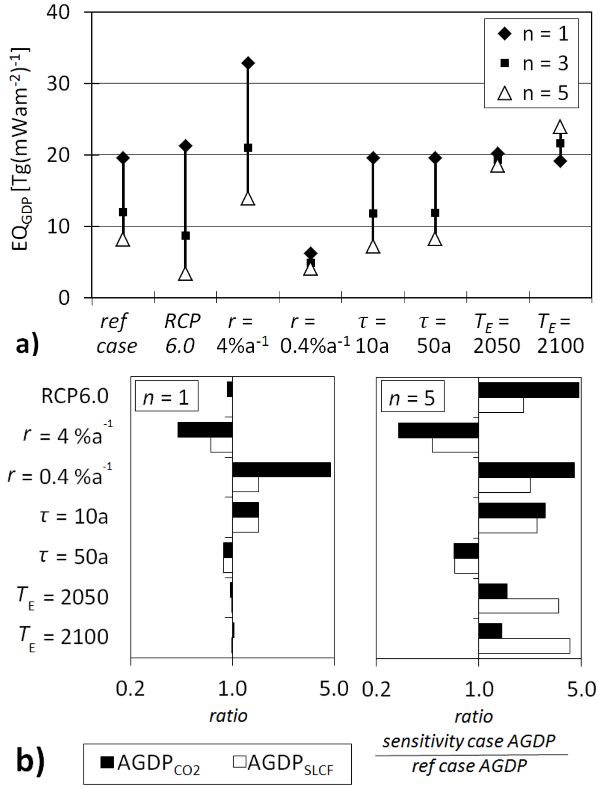

Figure 4.1: *(a) Economic forcing-based CO_2 equivalence factors (EQ_{GDP}) to calculate CO_2 equivalences for SLCF for different damage function exponents $n = 1, 3$ and 5 in the reference case and sensitivity to selected input parameters (background concentration pathway RCP6.0, discount rate $r = 4\,\%\ a^{-1}$, $0.4\,\%\ a^{-1}$, climate response time $\tau = 10\,a, 50\,a$, point in time of emission release T_{EM} = 2050 and 2100. (b) Changes of the absolute global damage potentials as ratios to the respective reference cases for CO_2 and SLCF and for n = 1 and n = 5, resulting from changes in the parameters indicated at the ordinate. Note that the abscissa is scaled logarithmically. Underlying data are given in Appendix, table A.4, page 122)*

equivalence factors. When comparing a discount rate of 4 % a^{-1} to the reference case (r = 2 % a^{-1}; Fig. 1b), the damage induced by long-lived CO_2 is reduced more strongly than that of SLCF, resulting in an increase of the by a factor of around 1.7. At the same time, the convexity of the damage function decisively controls EQ_{GDP}.

When attaching more importance to damages in the far future by applying smaller discount rates (r = 0.4 % a^{-1}), an opposite trend is noticeable: more than halves compared to the reference case. The functional form of the economic damage function becomes less important.

Point in time of emission release

Since the non-linearity of the economic damage function interferes with the future concentration pathway we go one step further and analyse the performance of under different levels of concentration and over time. We look at emission releases in 2050 and 2100 on the basis that background CO_2 concentrations are expected to stabilise in mid-term and decline thereafter, according to the RCP2.6. Thus, a perturbation in 2050 takes effect on a stabilising CO_2 background and in 2100 it is evaluated against declining CO_2 concentrations.

The sensitivity of to the convexity of the damage function is most pronounced for 2005 emissions (Fig. 1a). It is negligible in 2050 and becomes slightly more relevant again in 2100 albeit in the opposite direction. While in 2050 background saturation and convexity effects almost level out, in 2100, the spectral saturation effect of CO2-induced RF is no longer of relevance. The non-linearity of the damage function emphasises the effect of SLCF and leads to a larger EQ_{GDP}.

To take another perspective, we focus on over time (T_{EM} =2005, 2050, 2100), given a specific damage function n. Assuming a linear damage function (n = 1), the SLCF-induced and CO_2-induced damages and thus the EQ_{GDP} factor remain largely constant over time. This is due to the fact that CO_2 spectral saturation effects are small. However, when n = 5, the SLCF-induced damage ($AGDP_{SLCF}$) more than triples for T_{EM} =2050, and quadruples for T_{EM} =2100, compared to 2005, while the CO_2-induced damage ($\mathrm{AGDP}_{\mathrm{CO_2}}$) only grows by a factor of around 1.5 (2050, 2100). Thus SLCF substantially gain in importance (Fig. 4.1b).

Physical forcing-based CO_2 equivalent factors

Physical metrics are simpler in construction as constant atmospheric background conditions and a linear damage function are assumed. Consequently, the respective CO_2 equivalences are easier to determine than those that are economic-based. We compare the performance of physical forcing-based factors in relation to the range of reference case (Fig. 4.2). We consider different time horizons for physical metrics ($H = 50$ a, 100 a, 50 a), and vary discount rates for the GDP accordingly ($r = 4\,\%\,\mathrm{a}^{-1}, 2\,\%\,\mathrm{a}^{-1}, 0.4\,\%\,\mathrm{a}^{-1}$). For emissions in 2005, irrespective of the discount rates, all physical forcing-based factors are within the span of values calculated for the economic factors based on $n=1$ and n = 5.

The comparability between the physical and economic factors depends on atmospheric concentrations trends (Fig. 4.2). For emissions in 2050, with larger atmospheric CO_2 background concentrations than in 2005, the physical-based factors turn out to be slightly greater than in 2005, being equivalent to the with a linear damage function. For emissions in 2050, the physical-based factors with discounting come close to the range of but are slightly higher since they consider constant atmospheric concentrations. Physical-based factors with a finite time horizon put considerably more weight on CO_2 than EQ_{GDP}.

For emissions in 2100 however, with atmospheric CO_2 concentrations lower than in 2050 and against declining concentration levels, the physical factors favour the long-lived CO_2 over with $n > 1$. The gap between physical and economic-based factors becomes more pronounced with stronger non-linearity of the damage function and a finite time horizon rather than discounting.

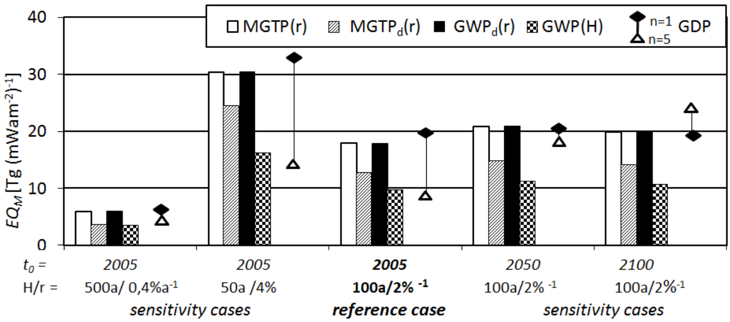

Figure 4.2: *Physical (bars) and economic (vertical lines with symbols) forcing-based factors to derive CO_2 equivalences for SLCF: reference case (centre) and sensitivity cases for different discount rates r and corresponding time horizons H (left) and for different times of emission release (right).*

For physical-based factors, the unit step function with a finite time horizon H puts more emphasis on long-lived climate effects than discounting with a rate r, if $r = 2/H$. This is valid for all considered discount rates and times of emission release. Further, with RF as impact proxy, the gap between physical and economic CO_2 equivalences for SLCF is more pronounced than with ΔT as a proxy, due to its different impact characteristics along the temporal axis.

4.3.2 Practical Application

We now apply the generalised approach presented above to calculate activity- and fossil fuel-based CO_2 equivalence factors for the practical example of aviation-induced cloudiness.

Scaling the generic reference case results (with E_{SLCF} = 1, appendix table A.2 121) with RF_{con} in the year 2005 (11.8 mW m^{-2}) provides RFs equivalence to 96.8 and 231.3 Tg_{CO_2e} a^{-1} for a highly non-linear (n = 5) and a linear damage function, respectively. Normalising this reference quantity either to the global aviation fuel burn or to the annual flight distance, the corresponding combustion and activity-related economic factors to derive CO_2 equivalences for contrails (EQ_M^{FFE}, EQ_{GDP}^{A}) amount to 0.13 and 0.32 kg_{CO_2e} $(kg_{CO_2})^{-1}$, and 2.3 and 5.8 kg_{CO_2e} (km)$^{-1}$ for $n = 5$ and 1, respectively (Fig. 4.3). Factors to derive CO_2 equivalences for contrails based on other metric types can be derived accordingly (appendix table A.3, 122).

In a second step, we introduce efficacy-corrected values and include contrail cirrus into the analysis. These SLCF specific adjustments linearly scale all types of factors including CO_2 equivalences. The large uncertainty bandwidth with respect to E_{con} from 0.3 (Rap et al., 2010) to 0.59 (Ponater et al., 2005) might reduce the reference case contrail factors down to one third. When including contrail cirrus, EQ_M easily triple, with an uncertainty range which has the potential to increase them by up to a factor of eight ($RF_{con} = 10.8$ mW m^{-2} $\rightarrow$ RF_{cirrus} = 33 to 87 mW m^{-2}). Additionally, though not considered here explicitly, uncertainties in fuel and activity inventories affect the related factor types EQ_M^{FFE} and EQ_M^A, respectively.

Sensitivities of contrail (Fig. 4.3) reveal that including contrail cirrus and the contrail-specific efficacy result in a larger value range than the damage function considered and future scenario assumptions. Scientific and value-based uncertainties are larger than uncertainties, related to the scenario and the damage function.

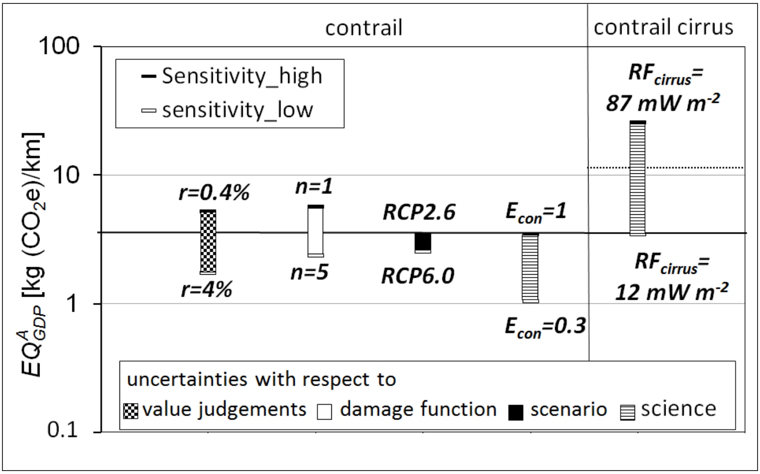

Figure 4.3: *Activity (Distance)-based CO_2 equivalences factors* EQ^A_{GDP}. *The solid (rightmost dashed) line represents the reference case (n = 3) for linear contrails (contrail cirrus including linear contrails). Sensitivities to the discount rate r, the damage function exponent n, the atmospheric background scenario, and the efficacy E_{con} are displayed. The pattern represents the origin of uncertainty*

4.4 Discussion

We presented three types of metric-based factors to derive CO_2 equivalences for SLCF. Due to its generalised form, the forcing-based factor (EQ_M) can be applied to any type of SLCF because it depends on the metric concept and input parameters, but not on the nature of the SLCF. By contrast, the efficacy-corrected activity-based and fossil fuel-based types ($\mathrm{EQ}_\mathrm{M}^\mathrm{A}$, $\mathrm{EQ}_\mathrm{M}^\mathrm{FFE}$) are specific to particular SLCF. They can be used to derive CO_2 equivalences for SLCF from activity data or concurrent CO_2 emissions, and thus are most meaningful for practical applications.

Numerical values

The economic forcing-based factors computed by means of the LinClim model for a variety of parameter assumptions range from 3 to 33 $(\mathrm{Tg_{CO_2}\,a^{-1}})\,(\mathrm{mWm^{-2}})^{-1}$ in 2005, with a best estimate of 8 – 20 $(\mathrm{Tg_{CO_2e}\,a^{-1}})\,(\mathrm{mW\,m^{-2}})^{-1}$ in 2005, in the face of ambitious climate policies and a discount rate of $r = 2\,\%\,\mathrm{a}^{-1}$. The factor of 2–3 between the lower and upper bound represents the damage function-related uncertainty. The scenario-related and damage-related uncertainty that is considered explicitly by economic metrics only, tends to be smaller than value-based uncertainty. A pragmatic way to handle this uncertainty is to agree on a best estimate input assumption to determine the factor for present-day applications, and to re-evaluate the factor in the future. Future updates of equivalence factors should take into account input parameters adjusted according to new scientific knowledge, observed atmospheric background conditions and well-founded changes in value judgements.

Sensitivities of individual parameters

The generic factors are most sensitive to the choice of the discount rate, the degree of convexity of the damage function and future atmospheric background conditions. While the time constant of the climate system plays a minor role, SLCF-specific uncertainties (E_{SLCF}, $\mathrm{RF_{SLCF}}$) have the potential to substantially exceed the metric related policy choices. These findings are in line with the results of other studies (e. g. Dorbian et al., 2011; Boucher, 2012).

4.4.1 Global mean versus regional differentiated perspective

Our straightforward approach based on average global mean RF highlights the consequences of metric decisions on the relative weighting of SLCF andCO_2 and facilitates the implementation of selected climate policy instruments (e.g., emission inventories and carbon footprints). However, methodological limitations arise from the comparison of two structurally different types of climate impacts. On the level of policy implementation, there are concepts for addressing SLCF and LLCF separately by the 'multi-basket approach' (e. g., Rypdal et al., 2005; Jackson, 2009; Smith et al., 2012). Some studies (e. g. Rypdal et al., 2005; Berntsen et al., 2006) argue that by using global mean RF as a proxy for climate impacts from SLCF, important information on the spatial variability is lost and that cancellations may hide the importance of a differential regional impact structure for global climate change, particularly in the face of a non-linear damage function (Lund et al., 2012).

The starting point for a regional perspective on the emission-impact relation of SLCF could be the Specific Forcing Pulse (Bond et al., 2011). Such a disaggregated perspective is indispensable for the evaluation of instantaneous emission situations (e.g. changes in flight routes to mitigate contrails) as background atmospheric conditions crucially determine the outcome. Even though the regionally differentiated perspective required for designing adequate incentives in an individual emission situation e. g. through emission pricing and emissions trading, has the potential to substantially change the framework for mitigation strategies (e. g. Frömming et al., 2012), the effects are still poorly understood (e. g. Boer and Yu, 2003). We argue that, at a later stage, when an improved scientific understanding of regional climate change is available, the presented factors could be adjusted accordingly.

Physical-based versus economic-basedCO_2 equivalences

We find that the physical and economic metrics, where there is a relationship of $H = 2/r$, result inCO_2 equivalences of similar size. However, there is no consensus on this issue: Azar and Johansson (2011) use the relationship $r = 1/H$ while (Dorbian et al., 2011) argue that there is no commensurate way of balancing the two weighting functions. The relationship determines the correlation between CO_2 equivalences based on different metric types and thus whether a physical metric-based CO_2 equivalence with a finite time horizon has the potential to approximate economic-based ones for a given atmospheric state.

4.4.2 Normative value judgements

The fundamental challenge of comparing CO_2 and SLCF lies in the need to agree on appropriate normative and policy frameworks. While challenge applies to other greenhouse gas emission metrics as well, it becomes amplified in the case of SLCF due to the need to compare two fundamentally different types of climate effects. In this case the level of scientific uncertainty rises substantially and the trade-off between simplicity and operational feasibility, a common dilemma in metric design, becomes even more pronounced. In addition, value judgements gain in importance.

4.5 Conclusions

The objective of this article is to provide a basis for calculating CO_2 equivalences for SLCF and to determine their sensitivity to input variables, underlying assumptions and value judgements. The metric-based factors presented, referring to the reference quantity of global mean RF, provide a pragmatic approach for comparing the climate effects of CO_2 and SLCF. The main findings are:

- Due to the equivalence of their temporal forcing patterns, SLCF can be treated generically when calculating CO_2 equivalence.
- Under our reference case assumptions ($r = 2\,\%\ a^{-1}$), the economic damage caused by 1 mW m^{-2} RF_{SLCF} lies in the range of 8 – 20 $Tg_{CO_2e}\ a^{-1}$.
- The evaluation of SLCF tends to be more sensitive to SLCF specific physical uncertainties and the normative choice of a discount rate than to the underlying metric approach *M* (GDP, GWP, MGTP).
- Effects from non-linearity of the economic damage function depend on the atmospheric background trends: they may be negligible (constant atmospheric conditions), or may emphasise either SLCF (increasing) or CO_2 (decreasing atmospheric background CO_2 concentrations). The effects become particularly important in short-term strategies or in the face of strongly increasing CO_2 background concentration scenarios (e. g. RCP6.0) but are of minor importance in a long-term stabilisation strategy (RCP2.6).
- The ability of physical metrics to approximate economic-based metrics depends on atmospheric concentration levels and trends.
- In the face of a distinct non-linear damage function a cost-efficient climate stabilisation strategy requires increasing CO_2 equivalence factors for SLCF over time.
- Using the unit step function with a finite time horizon results in smaller CO_2 equivalences for SLCF than achieved through discounting.

The application to contrails suggests:

- In the reference case (year 2005, $E_{con} = 1$), allowances of 1.13 and 1.32 kg CO_2e for $n = 5$ and 1, respectively, are required to offset the annually and globally-average climate damages of CO_2 and contrails per kg CO_2 emitted in aviation.
- Contrails are responsible for 2.3 and 5.8 kg CO_2e per average flight-km for $n = 5$ and 1, respectively. The methodology, however, does not provide CO_2 equivalences for a flight-km in an individual flight situation.

Under our reference conditions, physical CO_2 equivalences for SLCF are in the same order of magnitude as economic ones for the coming decades. The latter, however, provide detailed insight into structural uncertainties of the CO_2 equivalences and provide an evolution of CO_2 equivalences over time that is more in line with cost-efficient climate stabilisation.

4.6 Acknowledgements

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Chapter 5

The negotiation process to include international aviation in a post–2012 climate regime

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5.1 Introduction

The central challenge facing a post-2012 climate regime is to establish a commitment architecture that comprehensively takes into account the objective "to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC)). Based on the scientific findings of the Third and Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001, 2007a,c,b), the European Union (EU), the Group of 20 and many other governments agreed on the target that the global annual mean surface temperature increase should be limited to a maximum of 2 °C above pre-industrialized values (Council of the European Union, 2005; Point Carbon, 2009a,b).

As an initial attempt to address risks posed by global climate change, the Kyoto Protocol's first 5-year commitment period officially began in January 2008. In December 2007, the international community came together in Bali to craft a two-year roadmap to guide work in developing a post-2012 agreement. This roadmap, officially referred to as the Bali Action Plan, identifies a number of issues that negotiators will have to address to achieve a successful agreement at the 2009 Copenhagen climate change conference.

Emissions from bunker fuels, i. e. emissions from fuel used in international aviation and shipping, play a special role in international climate policies. They are excluded from the binding absolute emission targets in the Kyoto Protocol. They are one of the fastest growing sources of greenhouse gas emissions; the sector's CO_2 emissions grew by 2.6 % p.a. and 48 % in total between 1990 and 2005, amounting to a CO_2emission level of around 960 Tg CO_2 in 2005 (World Resource Institute, 2009). CO_2emissions from bunker fuels are thus in the same order of magnitude as the emissions level of Germany, a large industrialized country (2007: 841 Tg CO_2 (European Environment Agency, 2009)). International aviation is responsible for around half of CO_2 emissions from bunker fuels and its CO_2 emission growth rates are similar to the bunker fuel's average (IEA, 2008).

While industrialized countries, i. e. Annex I countries, which have ratified the Kyoto Protocol, are obliged to reduce the total emission of all other sectors by about 5 %, the emission growth of bunker fuels can significantly impair global reduction efforts in other sectors. As a consequence, other sectors have to make even more significant reductions in emissions in order to achieve the 2 °C target (Anderson et al., 2006; Bows et al., 2009). In the EU, there is the risk that growth in the Community's share of aviation emissions could by 2012 offset more than a quarter of the environmental benefits of the reductions required by the EU target under the Kyoto Protocol (European Commission, 2006).

Aircraft emissions released in high altitudes induce some significant non-CO_2climate effects e. g. caused by the production of ozone, the reduction of methane and the formation of contrails and cirrus clouds (IPCC, 1999). Current scientific evidence suggests that in aviation the sum of all radiative effects may exceed by a factor of 2 to 5 the radiative effect of CO_2 alone (Sausen et al., 2005; Lee et al., 2010); however, considerable scientific uncertainties remain with regard to the non–CO_2 effects. Methodological difficulties in comparing short- and long-lived radiative effects and gases are particularly apparent in the aviation sector (Forster et al., 2006; Rypdal et al., 2005). In the negotiation process the focus is laid on limiting the global, long-lived greenhouse gas CO_2. At this point in time, considering non-CO_2 effects forms an additional hurdle with the potential to disrupt the whole negotiation process. A transitional arrangement from initial inclusion of CO_2 only to coverage of climate impacts of all aviation emissions once there is a clear scientific basis seems to be the best way forward.

The objective of this article is to evaluate the current negotiation process on limiting emissions from international aviation and to identify a future policy framework which has both, the chance to be broadly supported and the potential to manage aviation emissions effectively. Against the background of the general political framework for a post–2012 climate regime, this article highlights the sector-specific challenges of international aviation. Possible options to include aviation in a post–2012 climate regime are outlined and evaluated in the context of past and current negotiation positions of different actors. The article provides a more detailed picture of a global sectoral policy framework in international aviation coupled with the possibility of climate financing. This approach is seen as a potential key to overcoming the political deadlock in the climate negotiation process in international aviation.

5.2 Political framework for a post–2012 climate regime

A fundamental requirement of any UNFCCC climate regime is to integrate countries in the commitment structure commensurate with their stage of development. This means that the "common but differentiated responsibilities and capabilities (CBDR)-principle" of developing and industrialized countries (Article 3 of UNFCCC) should be reflected in the type and degree of commitment. A future climate treaty to agree upon mitigation measures and to cope with adaptation will be negotiated on the basis of this principle.

In a post–2012 climate regime the commitment structures embedded in the Kyoto Protocol will probably be partly included; they are, however, discussed in a broader context. There is a move away from the historical division in "Annex I" and "Non Annex I Countries", opening the floor for new combinations and grades of commitments for developing countries (Watanabe et al., 2008). Diverse strategies for a post–2012 architecture have already been developed and discussed (e. g. Höhne et al., 2005; den Elzen et al., 2007; Höhne, 2006; Sterk et al., 2009; Members of the Non-governmental Organization Community, 2009). At this stage it is not conceivable how a post–2012 climate regime will finally be worked out. However, it can be assumed that the target for industrialized countries in 2020 will be in the range of 25 % –40 % greenhouse gas reduction compared to 1990. For developing countries, a reduction of 15- 30 % compared to "business-as-usual" is then needed to cope with science-based postulations of the 2 °C target (den Elzen and Höhne, 2008; UNFCCC, 2009; Gupta et al., 2007, p.776). While it is certain that advanced developing countries and developing countries will be treated in a different manner, it is still unclear how the reduction in the developing countries will be achieved (e. g. technology transfer, avoided deforestation) and, more importantly, who will finance this and with which institutional structures will the transfers be granted. Similar questions arise with regard to adaptation.

The UNFCCC and the Kyoto Protocol mandate Annex II Parties, OECD countries, to provide, among other things, financial resources to developing countries (Article 4.3 of the Convention, Article 11 of the Protocol). Negotiation practice in the climate protection process, however, has demonstrated that industrialized countries often showed great resistance to the granting of substantial financial transfers to developing countries as long as the developing countries are not willing to monitor comprehensively the investments and accept an appropriation of the funds for specified purposes.

The amount pledged or to be committed from Annex I Parties for climate financing remains far too low to meet the scale of the financing needs of developing countries in relation to climate adaptation and mitigation (Hepburn, 2006; South Centre, 2009). As an example, the operationalisation of the Adaptation Fund which is to finance concrete adaptation projects had for years been caught up in a wrangle over its institutional arrangement (Watanabe et al., 2008, p.150). In a post–2012 climate regime it is consensual that new, additional, also to existing Official Development Assistance flows, predictable and sustainable financial resources must be made available to support and finance various challenges of development. It is discussed how these financial resources can be raised and to what extent public or private investment is needed. It is apparent that innovative policy approaches are required as the need for adaptation funding by far exceeds the revenues which could be raised by domestic taxation (Müller and Hepburn, 2006). The financial transfers from industrialized to developing countries, however, are crucial for the future South-North relationship.

In return, since the Bali Conference in 2007, the developing countries have been willing to participate more actively in a future climate regime, a long-standing postulation by some Annex I Countries, most prominently by the United States of America. According to the Bali Roadmap, all developed Parties have to reduce their emissions “quantitatively and in a comparable way” while developing countries have to make “their contribution to global emission reduction with the support of developed countries in a measurable, reportable and verifiable manner” (UNFCCC, 2008; Watanabe et al., 2008) see in the Bali Conference a significant shift in the battle lines, a rearrangement of positions and alliances that might well announce a decisive new era in global climate policy. They come to the conclusion that forging an alliance between North and South will be the key to successful negotiations on a post–2012 climate regime.

5.3 Specific challenges to including aviation in a binding global climate regime

Emissions of international aviation are excluded from the binding absolute emission targets in the Kyoto Protocol. The transboundary nature of international aviation and the participation of international and domestic players cause several sector-specific challenges which make equal treatment with other sectors difficult.

5.3.1 Assignment to Parties

The question of emission assignment to Parties was pivotal to the non-integration of the sector in the Kyoto Protocol. Since in international aviation at least two states are involved, assignment could not be made according to the territoriality principle as in other sectors. Eight assignment options have been proposed by the Subsidiary Body for Scientific and Technological Advice. Later, however, only four of them – despite the status quo, i. e. no assignment at all – were considered to be feasible (UNFCCC, 1996, 1997). They have been evaluated comprehensively in research in recent years (e. g. Nielsen, 2003; Wit et al., 2005b; Faber et al., 2007). In spite of data-related uncertainties, these assignment options have been proved realizable in practice, showing only slightly different distributional effects (Owen and Lee, 2005; Lee et al., 2005). The Parties are in a position to appraise their implications both for themselves and for the commitment architecture of a future climate regime. In theory, assignment to Parties is a reasonable solution. A prerequisite in practice, however, is that the international community agrees on a commitment structure providing for assignment to Parties, going hand in hand with a particular institutional setting. There are, however, sound arguments against allocating CO_2 emissions from international aviation to Parties and instead striving for a sectoral approach in international aviation, in which the assignment to Parties is superseded, see Section 5.4 and 5.5. To conclude, assignment to Parties represents more than a technical challenge; it is part of an institutional setting which could be agreed upon if political will prevails. The assignment itself should not be responsible for a political deadlock.

5

5.3.2 Institutional setting and principles

Article 2.2 of the Kyoto Protocol obliges Annex I countries to pursue limitation of greenhouse gas emissions from international aviation by working through the International Civil Aviation Organization (ICAO)[1]. In contrast to other sectors, there is a dual responsibility: UNFCCC discusses the issue of assignment whilst ICAO is responsible for the development of effective climate policies and measures.

In 2004, the ICAO General Assembly endorsed the concept of an open, voluntary emissions trading scheme in international aviation (ICAO, 2004; ICAO and CAEP, 2004; ICF Consulting and CE Delft, 2004; Scheelhaase and Grimme, 2007). However, steps towards the implementation of an international emission trading scheme have not, as yet, been taken. Dissatisfaction over this failure by ICAO has prompted the European Commission to develop an amendment to the European Emissions Trading Scheme (EU ETS) that includes all aircraft operators flying in

[1] ICAO codifies the principles and techniques of international air transport. In order to ensure safe, secure and sustainable civil aviation, it fosters the planning and development of the international aviation market by setting standards. These standards, developed on a cooperative basis among its Member States, are uni-form on a global level.

and out of Europe from 2012 onwards in the trading scheme, see Section 5.4.3. The 2007 General Assembly of ICAO adopted a critical attitude towards this scheme and urged Member States not to apply an emissions trading system on another state's airlines "except on the basis of mutual agreement between those States". In response to this Assembly Resolution, all 42 European Member States of ICAO entered a formal reservation and stated that they did not intend to be bound by it (ICAO).

In view of the climate summit in Copenhagen in 2009, the ICAO Assembly set up in 2007 the Group on International Aviation and Climate Change (GIACC). The Group, with equitable participation of developing and developed countries was charged to develop an action plan targeted at the reduction of aviation emissions. In summer 2009, the GIACC recommended non-binding fuel efficiency goals of 2 % per annum. This represents in the minds of many little more than "business as usual" and would not deal with the emissions rise caused by a projected annual increase of 5 % in air traffic. Longer-term targets of aviation carbon neutral growth by 2020 or of actual emission cuts were discussed without agreement. These few ambitious targets can be seen as a missed opportunity for ICAO to show leadership. The plan is not a credible basis for the Copenhagen Agreement as it lacks the essential elements of any climate strategy: a base year for measurement and a target for emission reduction in absolute terms. In sum, consensus at the global level through ICAO on the introduction or use of economic instruments has not been reached thus far (Lee et al., 2009). From the European perspective, the climate policy-making process in ICAO is rather slow and deficient. Over the past decade, work performed within the ICAO has not resulted in concrete actions to address appropriately the growth in emissions.

According to (Oberthür, 2003), the lack of action at ICAO has so far not been made up for by measures within the climate change regime. An important motivation for efforts of ICAO is the potential regulatory competition with the climate change regime. However, the UNFCCC process on limiting emissions from bunker fuels is also sluggish. In the past, Organization of Petroleum Exporting Countries (OPEC) countries and the United States of America blocked negotiations on bunker fuels much more than in any other sector. Moreover, developing countries were also not urging developed countries to introduce effective mitigation policies in international aviation. Thus, given the lack of political will to limit emissions from bunker fuels within the UNFCCC, the motivation of potential regulatory competition has not been very forceful.

Furthermore, the choice of emission assignment regulation and the corresponding commitment architecture have immediate implications for the set-up of policies and measures, and vice versa.[2] Thus, for effective climate policy, these negotiation issues have to be treated together (Faber et al., 2007). A close coordination of UNFCCC and ICAO could contribute to a forward-looking policy process. However, in practice the two institutions are hardly linked. In theory, almost the same contracting states are represented in both organizations; the

[2]Some countries are Parties to the UNFCCC but not to ICAO and vice versa.

missing link is mainly due to inconsistent policies in countries with diverging positions of transport and environment ministries. Furthermore, co-operation is made difficult as the institutions have strongly diverging priorities and principles. One aspect exemplifying the different positions is the attitude towards unilateral action such as the inclusion of aviation in the EU ETS. Unilateral action turns out to be a strong driving force for an ambitious climate regime. It is generally in line with the principles and visions of UNFCCC. ICAO, however, is strongly opposing it.

ICAO aims for a policy framework which treats all actors in the same way. The framework shall be uniform on a global level in order to avoid market distortion in the highly competitive air transport market. ICAO's institutional principle, however, appears to run counter to the CBDR principle of UNFCCC. In fact, the application of this fundamental principle of the UNFCCC process in the aviation sector represents a great challenge. The CBDR principle was set up to reflect differences in national circumstances of the countries and different historical responsibilities for climate change. The most relevant aspects influencing the responsibility for climate change and capability to cope with it are the economic structure of the country, which is closely related to the emission reduction potential and its costs, the historical responsibility, the stage of development, the vulnerability to climate change and the dependency on the export of natural resources (Höhne, 2006). International transport, however, differs from ground-based emission sources. It contributes to economic development by linking different economies and allowing economies to exploit comparative advantages. For example, in 2008, Emirates (Dubai), Singapore Airlines (Singapore) and Cathay Pacific Airways (Hong Kong) were the 4th, 5th and 6th largest airlines in the world with regard to international scheduled passenger-kilometres flown (IATA, 2008). They are highly competitive global players with considerable market shares. The economic benefit of the hubs Dubai, Singapore and Hong Kong is facilitated by a favourable geographical location to interconnect different economic regions. The performance of the aviation industry is only limitedly related to the structure of the economy and historical responsibility. Due to the non-national nature of international air transport activities, it is not necessarily correlated with the economic performance of the nation state to which the transporting company belongs or in which fuel is sold.

In conclusion, the operationalization of the CBDR principle in the aviation sector plays an important role in the political debate and provides leeway within the negotiation process. A more subtle distinction of responsibility and capability could be a door opener to finding innovative negotiation solutions.

5.4 Negotiation process for including aviation in a post-2012 climate regime

5.4.1 Possible Policy Approaches in the Aviation Sector

Realizable and feasible ways in which international aviation transport could be incorporated in a post–2012 climate regime are outlined comprehensively in Faber et al. (2007). In a multi-criteria analysis three approaches scored best: a global solution including the national level, a global sectoral approach and a regional start. They are described in the following.

Assignment to Parties and stacked Policies and Measures

In this approach, emissions are allocated to the country of arrival or departure of the aircraft and are included in national emission totals. The route-based assignment option is chosen on the one hand as the market distortion and possibilities for evasion would be less compared with other options and on the other hand it reflects well the economic benefit of linking economies. In order to allow for differentiated commitments according to the CBDR principle, the targets as well as the policies and measures are stacked: all countries introduce, for instance, technology standards or agree to phase out "climate-unfriendly" subsidies. In addition, advanced developing and industrialized countries have to comply with intensity targets, i.e. by implementing performance standards and emission charges. In addition, industrialized countries commit themselves to absolute emission targets, preferably by establishing an emissions trading scheme. The policies address direct Kyoto-gases only; flanking measures are intended for indirect greenhouse gases. In this approach, UNFCCC as central actor is responsible for setting the national targets and enforcing them. ICAO develops guidance on policies and measures while the countries coordinate and implement them.

Sectoral Approach

A variety of sectoral approaches is possible. They have in common that emissions are not allocated to countries but to the sector itself. In the sectoral approach favored in the analysis by (Faber et al., 2007), the UNFCCC assigns responsibility for the sector emissions to the ICAO. ICAO implements an emission trading scheme and sets a cap which is in good agreement with UNFCCC policy targets in other sectors, providing the basis for an inter-sectoral linkage of trading schemes. The differentiation of responsibilities according to the CBDR principle should be route-based; however, how the final design works out is a matter of negotiation.[3] ICAO plays a key role in this institutional set-up while

[3] One way of implementing this differentiation would be to require operators to surrender allowances on specific routes only i.e. in and between industrialized and advanced developed countries. Another way

aircraft operators surrender allowances and nation states are responsible for the compliance of aircraft operators with the policies.

Alternatively to a global scheme harmonized with UNFCCC policy targets, a different sectoral commitment was discussed, consisting of pledges agreed under ICAO to contribute to mitigating climate change. This is in line with the current tasks and responsibilities of ICAO and could therefore build on the existing organizational capacities. Second, there would not be a direct need for differentiating commitments, since commitment could be made without reference to the UNFCCC's CBDR principle. However, the participation of developing countries is exceedingly doubtful if their specific interests are ignored. Furthermore, in view of the past, the question arises whether ICAO is capable of introducing stringent climate policy measures. The type of policies and measures most likely to be introduced by ICAO would be technical regulations, with potentially more stringent measures likely only on a voluntary basis, at best. Given the projected growth, a stabilization or absolute reduction of emissions seems unlikely for a sectoral commitment outside the UNFCCC. Against this background, Faber et al. (2007) consider this approach to be inferior to one which is harmonized with the UNFCCC policy framework.

Regional Start

In case international aviation is not incorporated in a global climate regime, groups of nations will implement political measures for limiting the climate impact of international transport. Using the example of the EU ETS and its possible expansion beyond European nations, (Faber et al., 2007) evaluate the potential of such a regional start. The regional start is only second best as aspects of equity and a broad coverage are not guaranteed. It is not addressed in detail here since a regional start will only be considered a favourable option if a global solution fails to be achieved.

There are numerous criteria for assessing the different approaches: environmental effectiveness and economic efficiency aspects but also practical and political criteria addressing e. g. equity and the polluter-pay-principle. The global approaches are both effective and score best based on these criteria. They could minimize market distortion while at the same time maximizing the environmental effect by facilitating broad participation. Avoiding market distortion in the competitive international aviation market is one of the major key factors for political acceptance. In any case, a route-based system seems to be the best approach as effects on the competitive positions of airlines can be kept small, also a lesson learnt from the EU ETS (Wit et al., 2005a). Furthermore, the linkage to the overall climate regime in terms of the international carbon market seems to be a prerequisite for binding ambitious targets in the aviation sector. As long as the environmental integrity of the overall climate regime is ensured, emis-

would be to require operators to surrender allowances for all their emissions on routes in or between industrialized countries, for a part of their emissions on routes in or between advanced developing countries and no allowances for routes in or between least developed countries (Faber et al., 2007).

sion growth in aviation can be accepted. In both global approaches, the CBDR principle is taken into account on the level of policies and measures. However, looking at the overall global policy framework (see Section 5.2), it is questionable whether the proposed differentiation sufficiently meets the needs of developing countries. The two global approaches differ mainly with regard to the institutional set-up, namely the role of ICAO and UNFCCC, the coverage as well as the addressee of assignment; all of them critical matters for negotiation in the past (see Section 5.3).

In practice, many influential actors in the negotiation process, including the aviation industry, endorse the global sectoral approach. Section 4.2 provides a more detailed picture on positions of different actors in the negotiation process and section 5 outlines how the global sectoral approach could be coupled with the need of developing countries for climate financing. Which approach will be short-listed in future, however, depends not only on the benefits and drawbacks from aviation's perspective but also strongly on the overall negotiation process and principles and the overall commitment architecture in a post–2012 regime.

5.4.2 Nation state's positions

Positions of all countries in the climate negotiation are continuously evolving over time. With changing governments after national elections, with new scientific findings and gradually advancing climate change, attitudes toward global climate policy are subject to change. Starting with positions in the past Kyoto process, it will be shown how some Parties gradually shift their positions in the current negotiation process.

Several potent Annex I countries like e. g. the United States, Australia and Japan had been in favour of exemption of bunker fuels from the UNFCCC process. By supporting a global sectoral scheme under ICAO, the aspects of free competition and equal treatment of all states have been in the forefront. However, looking at the ICAO policy-making process in the past, demanding an ICAO-based scheme uncoupled from the UNFCCC process goes hand in hand with a global policy of the "least common denominator", in which a strong climate regime does not have priority.

With new governments coming into power in Australia in 2007 and in the US in 2008, positions towards climate protection have changed radically. In June 2009, Congress adopted the US Waxman-Markey Climate Change Bill, which regulates the set-up of an ambitious national CO_2 cap and trade scheme (United States Congress, 2009; Greenair, 2009). The upstream trading scheme, which should cut carbon emissions by 17 % from 2005 levels in 2020 and 83 % in 2050, indirectly also covers international bunker fuel sold in the US. However, the Climate Bill still has to be adopted by the Senate before it can be written into the law. In response to ICAO's failure to agree on a mechanism for dealing with international aviation greenhouse gas emissions, Australia has become the first country to formally propose that international aviation be controlled under a global sectoral agreement by the UNFCCC rather than by ICAO (Reuters, 2009).

Developing countries formed, in the past, the direct counterpart to the advocacies in favour of a global scheme under ICAO. They firmly supported the application of the CBDR principle under UNFCCC in the form of non-inclusion of developing countries. However, in contrast to climate negotiations in other sectors under the Kyoto Protocol, the non-Annex I countries showed little initiative when it came to demanding absolute emission reduction in air traffic by Annex I countries. This diffidence and partial blocking of negotiations can be traced back to the differing but mostly economic motives of individual groups of countries: the members of the OPEC fear a downturn in demand for kerosene; the Alliance of Small Island States (AOSIS) and many other developing countries are themselves very much dependent on air traffic: tourism, the import and export of merchandise as well as domestic transportation of merchandise. Moreover, there was little necessity to open air traffic to Clean Development Mechanism projects and thereby to financial transfers to developing and advanced developing countries since emission reduction potentials are very limited in their scope and rather cost-intensive compared with other sectors (e. g. energy production, waste treatment). Fundamentally, there is the fear that air transport will become more expensive as a result of the restriction on air traffic emissions and that demand for certain export goods such as tourism will fall, or that imported goods will experience significant price increases.

The positions of some developing countries, and especially of those developing countries which are most vulnerable to climate change like the AOSIS and the least developed countries (LDCs), are likely to change in the negotiation of a future climate regime. At the climate summit in Poznan in December 2008, the Maldives presented a proposal on behalf of fifty LDCs. As the LDCs have a strong interest in new and additional funding for adaptation, independent of bilateral replenishment, they launched a proposal suggesting an International Air Passenger Adaptation Levy (Group of Least Developed Countries, 2008). As only passengers are affected by the levy who have the capability of flying internationally, their defensive attitude towards a global scheme including flights from and to developing countries is gradually breaking down. They assessed the impact on tourism to be minimal. Furthermore, most of the governments are becoming increasingly aware of the findings by Stern (2007), that the costs of taking action to reduce greenhouse gas emissions now are smaller than the costs of economic and social disruption from unmitigated climate change. With advancing climate change, for some small island states the financial impacts of aviation mitigation policies on tourist mobility and trade appear to be minor compared with the costs of direct climatic impacts, the indirect environmental and societal change impacts (NEF and WDM, 2008; UNWTO and UNEP, 2008). Countries with emerging markets such as China, Brazil and Argentina, however, still oppose a global scheme and plead in favour of the CBDR principle on the mitigation side.

The political will among European decision-makers to address aviation emissions appears to be high as evidenced by the inclusion of aviation in the EU ETS (see Section 5.4.3). The EU is in favour of a global sectoral approach in which assignment to Parties is dispensable. Any action to reduce emissions should take into account the possible net negative impact on isolated regions, remote islands and LDCs. The European Council reiterates that Parties should commit themselves to working through ICAO in order to reach an agreement in 2010 and approved in 2011.

The European Commission and the Council of the EU are convinced that ICAO has the responsibility to facilitate the development and adoption of global measures by the end of 2011 (European Commission, 2009), (Council of the European Union, 2009). However, if at the end of 2011 ICAO fails to reach an agreement, the European Commission will endorse plans for emissions from international aviation to be allocated to Parties under the Copenhagen agreement, which will ensure comparable action by all developed countries (European Commission, 2009). Whether the Member States and the European Council will advance the Commission's view, however, is questionable.

The commitment architecture proposed by the EU (and Norway) is partially in line with the LDC proposal. Both the EU and the LDC proposal strive for a scheme including all global emissions. According to the polluter pay principle, the responsibility should be assigned to air passengers on a personal level and not on a national country level. Different treatment of developed and developing countries should be accounted for in the form of financial compensation through revenues. In contrast to the LDCs' proposal on a levy, the EU, however, is in favour of an emissions trading scheme with auctioning. The aviation sector should be treated consistent with a global reduction path towards meeting the 2 °C objective, notably with reduction targets of 10 % reduction below 2005 levels by 2020 (Council of the European Union, 2009, p.7). The EU attaches importance to ensuring the environmental effectiveness whereas the aviation levy can also be designed as a purely revenue raising instrument without a (significant) impact on emissions.

5.4.3 Role of the European Emission Trading Scheme in aviation

For more than a decade the international community could not agree on concrete climate measures or targets for emissions from bunker fuels. Due to the political deadlock, the European Community finally decided to go ahead by including CO_2 emissions from all flights within, from and to the EU in the EU ETS from 2012 onwards. On the basis of a feasibility study (Wit et al., 2005a), the European Commission put forward a draft proposal in December 2006. The final Directive of the European Commission and European Parliament (Directive 2008/101/EC) was adopted in 2008.

The European advance strongly influences the global negotiation process. From 2012 onwards, roughly 50 % of global CO_2 emissions from international aviation will be subject to a binding target, independent of a global consensus at the climate summit in Copenhagen. While the European Member States took decisions on the design of the scheme, the blocking attitude of non-EU countries has prevented them from joining the discussion on important design issues. As it is obvious that all countries have an interest in controlling aviation regulations concerning flights from their home destination, non-EU governments are under pressure to discuss mitigation options on a global level.

The EU ETS allows for the possibility of excluding flights departing from a third country to an EU airport if that country adopts measures for reducing the climate change impact of flights. The planned US cap-and-trade scheme could well qualify as such a measure, suggesting that flights departing from the US would be excluded from the EU ETS. However, the articulation between the US and EU scheme would possibly not be straightforward because the coverage applies to fuel purchase in the US rather than flights departing from a US airport. The implementation of different conflicting and potentially overlapping national and regional policies enhances the need for a harmonized climate regime in aviation which could significantly reduce the compliance costs (Greenair, 2009).

Many of the active aviation market actors are basically in favour of a global homogeneous regulation rather than a regional or national approach. They fear market distortion such as carbon leakage and they want to ensure equal treatment of all actors in accordance with the Chicago Convention. Although the EU ETS is route-based to ensure equal treatment of all airlines on the same route, there might be some market distortion between EU and non-EU airlines due to the fact that it is a regional approach (Scheelhaase and Grimme, 2007; CE Delft and MVA Consultancy, 2007). With the European Directive having been adopted, airlines with a large share of flights falling under the EU ETS have incentives to stand up for the negotiation of a global climate deal at the UNFCCC summit in Copenhagen. In sum, including aviation in the EU ETS might have increased the political pressure on non-EU governments and on the airline industry to limit the so far unrestricted growth of international aviation emissions.

5.5 A global sectoral approach in international aviation coupled with the need for adaptation funding

There is a strongly growing and evident need to mitigate and adapt to climate change and a need for climate financing. The beginning of rapprochement between developed and developing countries represents a promising point of departure for the inclusion of aviation in a post–2012 regime (see Section 5.2). Given the highly competitive global aviation market in which advanced developing countries play a significant role, new options within the commitment architecture are arguable. One expression of a new era in climate negotiation in which negotiation principles are adapted to the changing environment and challenges is the idea of a global approach in which the need for funding for mitigation and adaptation measures is combined with a revenue-raising instrument to reduce aviation emissions.

Faced with a potential patchwork of different national and regional schemes, along with a proposal from LDCs for a levy on international aviation, the aviation industry has thrown its weight behind a global sectoral approach. In 2009, the International Air Transport Association (IATA) called for a global sectoral approach. IATA believes that with some political leadership and innovation solutions, equal treatment between airlines and differentiated responsibilities for States are completely consistent in the context of international aviation (IATA, 2009). For the first time important business actors vehemently call for the inclusion of international aviation in a post–2012 climate regime. An industry coalition, the "Aviation Global Deal Group" (AGDG) comprising key airlines from Europe and Asia was formed as ongoing efforts to address aviation emissions have been largely unsuccessful. The Group's intention is to develop a practical, business-led solution that helps contribute to global efforts to address climate change. They argue in favour of a global scheme in which revenues are raised by auctioning. The Group suggests using auctioning revenues for climate change initiatives in the developing world and a proportion of the revenues to support low-carbon technology research and development programs in the aviation sector (Aviation Global Deal Group, 2009). The airlines' willingness-to-accept that revenue funds are spent predominantly outside the sector and do not inure to the benefits of neither their costumers nor the airline's country of origin prove that the Aviation Global Deal Group wants to take responsibility for the consequences of climate change, beyond their own financial interests. There is a real concern about tackling aviation emissions in a global sectoral scheme which includes all countries.

A global sectoral approach in international aviation designed to reduce or limit emissions and to raise revenues for adaptation at the same time creates differential treatment of countries through the allocation of revenues rather than by stacking commitments on the level of policies and measures. Müller (2006) and Agarwal (2000, p.6) provide important arguments for such an approach. Agarwal (2000) introduces the distinction between "luxury" and "survival" emissions, referring to per capita emission figures of developing and developed countries. There is no generally accepted definition of "luxury" emissions. It is, however, difficult to argue that international air travel emissions are "survival" emissions, and indeed a large proportion would probably be legitimately classified as luxury emissions. (NEF and WDM, 2008) has assessed that the highest income group are disproportionately responsible for emissions from aviation. This is true for both, developing and developed countries. (Müller and Hepburn, 2006) argues in the context of "luxury" emissions that there are good reasons for personalizing or denationalizing the responsibility, so that individuals are associated with responsibility for emissions, regardless of the sovereign territory on which they occur. Air passengers are responsible for emissions and reveal their economic capability by the ability of flying internationally. On ethical principles, it is therefore fair to ask all nations to address emissions from air travel in accordance with the CBDR principle. However, smaller developing island states, in which tourism constitutes a major branch of industry and provider of local employment, might argue, that individual travel is a "luxury", but that tourism as such, which goes hand in hand with emissions, is "survival".

There are several surveys (Brouwer et al., 2008; Hooper et al., 2008) that evaluate air passengers' willingness to pay to offset the climate impacts of their flights. Brouwer et al. (2008) found in a survey at Schiphol airport that 75 % of the air passengers are in principle willing to offset their greenhouse gas emissions, while differences are apparent depending on the home continent of the traveller. The motivation of air passengers who are willing to contribute stems from the recognition of responsibility and accountability of climate change as well as the genuine belief in the detrimental effects of climate change on future generations.

In practice, however, a minority of air travellers is currently offsetting. There is a large discrepancy between stated and revealed preferences. Brouwer et al. (2008) explain this gap between theory and practice due to the voluntary nature of offsetting programs. They argue that the willingness-to-pay increases if offsetting is mandatory which makes "free riding" impossible and if the effective use of revenues for climate change policy is guaranteed. According to Hooper et al. (2008) only a much smaller proportion of passengers is willing to offset. This proportion could, however, increase significantly if benefits of offsetting are reliably guaranteed. Furthermore, in the context of more robust and widespread climate change mitigation activity with standardized carbon markets as well as ambitious institutional responses to climate change, air passengers' willingness to pay would grow even more markedly (Hooper et al., 2008). The results of both surveys reveal that there are air travelers who are in principle supportive of measures that increase the cost of their travel based on the polluter pays principle. A prerequisite, however, is a robust, comprehensive and mandatory climate policy framework so that individual behaviour contributes in real terms.

At the same time, there is an urgent need to provide adequate, predictable and sustainable financial resources to assist developing Parties that are particularly vulnerable to the adverse impacts of climate change in meeting the costs of adaptation. The cost of adaptation in the developing world will be in the tens to hundreds of billions of Euros annually (Stern, 2007, p.442). Since potential revenues from a fiscal instrument in air traffic might generate annual financial resources in the region of billions, (Müller and Hepburn, 2006; Aviation Global Deal Group, 2009), its implementation could contribute in real terms. Furthermore, these revenues could easily exceed the resources of the Special Climate Change Fund, the LDC Fund and the Adaptation Fund, which were established earlier on.

In principle, it is debatable whether two central challenges of the negotiation process can be addressed successfully by one single instrument, particularly as it has proved difficult in the past to effectively address each challenge individually. However, moral and pragmatic reasons demonstrate that there are chances to overcome the political deadlock of the past by addressing the subjects simultaneously. Making funds available for adaptation is central to the North-South relationship and finally to the success of future climate regimes. Moreover, due to the genuinely international character of aviation, raising international funds is facilitated. Revenues are raised directly from the responsible and capable individuals without touching on domestic regulations. Climate financing could be the key to resolving the political deadlock between the need for effective global mitigation measures involving all global key operators (reflecting the ICAO principle) and the need for a differentiated treatment of countries according to their capability and responsibility for climate change (CBDR principle).

5.6 Summary and conclusion

In the past, limiting emissions from international air transport has proven to be politically exceedingly difficult, with sector-specific challenges hampering the negotiation process. The non-national nature of the emissions rendered the assignment to Parties difficult. The lack of political will and the institutional setting of the dual responsibility of UNFCCC and ICAO with strongly diverging principles adversely affected the political process. The operationalization of the moral obligation of CBDR under UNFCCC appeared to be in contradiction to the market principle of equal treatment of all actors under ICAO. This dilemma was clearly reflected in different negotiation positions of developing and developed countries in the Kyoto process.

Although the application of the CBDR principle is still one of the major challenges to be met, the situation does seem to have altered with regard to the post–2012 negotiations. UNFCCC, the EU, Australia, the Group of LDC, IATA and some leading airlines show a strong interest in including aviation emissions in a future climate regime. With the first steps taken in the Kyoto Protocol, with advancing climate change and with the growing need for adaptation and mitigation, negotiation positions change. A rapprochement between developed and developing countries can be observed, in the overall climate negotiations but also with regard to international aviation. If political will prevails, different policy approaches to include aviation in a future climate regime seem to be feasible, e. g. an assignment-based global scheme with stacked policies and measures, a global sectoral scheme in which assignment to Parties is indispensable or a regional approach. There are strong arguments in favour of a global sectoral scheme, but which approach is finally chosen depends largely on the overall negotiation process and commitment architecture.

A global sectoral approach in international aviation in which greenhouse gas emissions are limited while revenues for climate change purposes are raised, seems to be an attractive option. Such an approach may pave the way out of the past dilemma: it is generally in line with the CBDR principle under UNFCCC by providing the revenues predominantly to developing countries and it is consistent with the central postulation of ICAO, the equal treatment of all airlines. A global scheme in a highly competitive market is more likely to be accepted by industry than any regional approach. Revenues are raised from airlines which pass them on to their customers. This consistent implementation of the polluter-pays principle is, from an ethical and moral point of view, a very convincing and equitable strategy. However, raising revenues for developing countries might be part of the solution but it should not be at the expense of effective measures to tackle aviation's growing emissions. Absolute emission reduction targets are needed.

In order to implement a global fiscal scheme in international aviation there is definitely a need for stronger UNFCCC leadership and enhanced cooperation between UNFCCC and ICAO. In the Kyoto Protocol, Parties were charged to work through ICAO towards the development of policies and measures to limit the emissions of international aviation. Even though this UN organization seems to be predestined to implement policies in the international aviation market, the slow and non-committal policy-making process raises the question of the future role this institution will assume in a post–2012 climate regime. In sum, there is considerable leeway for negotiations on including aviation in a post–2012 regime: the targets themselves, the way the targets are achieved, the institutional setting and the role of aviation in the overall commitment architecture.

Chapter 6

Synthesis and Outlook

In view of the challenges in climate policies this thesis analyses climate metric concepts for trading-off short-lived climate forcers (SLCF) and CO_2, using the example of aviation. It contributes to the understanding of the inter- and transdisciplinary nature of climate metric design. Chapter 6 summarizes the starting points, the main contributions, draws some general conclusions and points out future research needs.

6.1 Overview of research hypotheses and questions

Starting points of this thesis have been three research hypotheses:

RH I Climate metric design requires interdisciplinary understanding and transdisciplinary co-operation between climate policy stakeholders.

RH II Metric values for trading-off SLCF and CO_2 are highly ambiguous. Choices in climate metric design determine decisively the relative weighting of SLCF and CO_2.

RH III In international aviation, there is particular need for agreeing on a tool to weigh perturbation with distinctively different atmospheric lifetimes.

These hypotheses are supported by the established climate policy process and the latest scientific findings. On the level of IPCC, the need for interdisciplinary co-operation in climate metric design was recognized (Shine, 2009; Plattner et al., 2009). Further, in scientific literature, the key function of policy decisions for climate metric design in line with mitigation principles, the transdisciplinary element, is consistently emphasized (e. g. Fuglestvedt et al., 2003, 2010; Tanaka et al., 2010, 2013). Climate metrics serve for evaluating trade-offs between different climate perturbations. The evaluation inevitably relies on both scientific aspects (understanding differences in climate effects of different GHG) and economic approaches (evaluating these differences). For comparing long-lived greenhouse gases, the policy-makers have accepted the GWP, a purely physical metric. When starting this dissertation, scientists were reconsidering the GWP. A multitude of metrics has been presented in literature, however, there have been only few meta-studies on climate metrics design that revealed the linkage between atmospheric and economic science aspects in the context of ethical value judgements.

In contrast to the GWP for long-lived GHG, a metric for trading-off SLCF and CO_2 has not been politically accepted so far. Instead, a large bandwidth of potential metric values for SLCF was presented e. g., for the case of aviation-induced cloudiness (Fuglestvedt et al., 2003, 2010; Forster et al., 2007; Aamaas et al., 2012). Including international aviation's CO_2 emission in a global climate agreement has failed up to the date of finalization of this dissertation. Even though non-CO_2 effects have a considerable share of the current climate impact in the aviation sector (>50 %), policies addressing SLCF are neither implemented nor expected to be so in near-term.

Insights from the scientific findings are picked up and discussed in the context of the three sets of research questions (see also RQ I–III in Section 1.4, page 14). RQ I was essentially handled in Chapter 2, RQ II and RQ III were explored in Chapters 3 and 4. Chapter 5 acts as a supplemental background analysis.

6.2 Climate metric design (RQ I)

How do the different scientific disciplines and stakeholders interact in climate metric design?

The assessments (Chapter 2 – 4) make transparent that climate metric design features a strong linkage between scientific, economic and policy relevant aspects.

The *scientific community* maps out the consequences of GHG emissions on the climate system (atmospheric scientists) and the socio-economic system (economic scientists) as a function of different future scenarios. Further, scientists develop criteria and highlight alternative options for an effective policy approach and mitigation strategy.

Based on the scientific support, the *policy– and decision–makers* are involved in the climate metric design by taking policy decisions and value judgements, societal priorities that go beyond descriptive science. These include the specification of

- the policy objectives and targets (e. g. meeting the 2 °C target, limiting long term climate change, limiting the rate of climate change)
- the policy approach (e. g. cost-benefit versus cost-effective policy framing),

- the weighting of impacts along the temporal axis (discount rate, time horizon)
- the assumed future scenarios in line with the envisaged policy target
- the aspects of climate and socio-economic system and principles in the mitigation strategy (fairness, efficiency, comprehensiveness, operational feasibility) that should be most prioritized.

The assessments illustrate that each metric requires and is based on this set of normative and policy decisions, even though most of the aspects are only reflected implicitly. In case the policy–maker takes explicitly the set of decisions, scientists are in a position to substantially constrain the set of scientifically recommended metrics. A joint understanding of the role of uncertainty, and consent on policy objectives and mitigation principles further facilitates the specification of an appropriate metric approach.

The methodological approach of this dissertation followed the inter- and transdisciplinary nature of the topic. Based on a sound knowledge of each of the relevant climate science disciplines and its limitations research was conducted with view on the policy-maker's perspective. The main challenge was to meet the discussion partners or audience at their level and disciplinary background, to outline different ways of thinking about the problem and to familiarize them with the importance of metrics for a cost-efficient multi-gas mitigation strategy:

- in the science community – the need for taking value judgements and real life solution for policy implementation and the economic perspective on a cost-effective mitigation strategy in line with a policy target;
- in the policy arena – the urgency to act, the interdependencies in the earth-climate system and the consequences of taking or delaying policy decisions;
- in the decision-making arena – benefits and limits of metric applications.

What are the underlying assumption, and explicit or implicit normative value judgements of the variety of alternative metrics proposed in the scientific literature? How can the multitude of emission-metrics presented in literature be classified and evaluated?

Climate metrics can be classified in a straightforward manner according to their impact and their weighting function. The economic meta analysis (Chapter 2) reveals that one of the primary criterion for the categorization of climate metrics, pivotal for its characteristic, are the (implicit) assumptions on the functional relationship between physical impact parameter and economic damage function. If there were perfect knowledge about climate impacts and a societal consensus about their evaluation, the Global Damage Potential (GDP) would be conceptually optimal approach to calculate climate metrics. The vast majority of climate metrics, including the Global Warming Potential (GWP) and Global Cost Potential (GCP) can be constructed as variants of this physico-economic metric (Section 2.3.3, Table 3.1, 27). Deviating assumptions on the economic damage function are taken either to simplify the metric (physical metrics, linear damage function) or to reflect policy priorities (a normative climate thresholds in the cost-effectiveness policy framing, GCP, θ_∞function).

The choice of metric is largely characterized by trade-offs between different kinds of uncertainties: explicit ones which are directly linked to operational feasibility and implicit structural ones which reflect the degree of policy relevance. Policy priorities determine the evaluation of these uncertainties.

What are the rationale, the benefits and the limitations of economic considerations in climate metric design?

Chapter 2 reveals that the assumed consequences on the socio-economic system are always reflected in a climate metric, however often only implicitly. The benefit of a physic-economic climate approach consists in the explicit illustration of uncertainties. The GDP reveals which aspects are relevant in the real world and offers transparency on consequences from policy decisions, value-judgements and scientific uncertainty on the relative weighting of climate effects. It illustrates that in face of changing atmospheric background conditions, an efficient weighting of climate effects requires a dynamically adjustable metric. Physico-economic metric concepts are best suited as benchmarks for simpler metric concepts and should guide future metric discussions. They are best qualified to link the metric to the overall policy framework (cost-benefit, cost-effectiveness) and disclose scientific and political alternatives in the face of future trends. Thus they are considered as pivotal for the interdisciplinary scientific discourse and for a consolidated transdisciplinary dialogue on climate metrics.

While physico-economic metrics perform the same functions as physical ones, the level of complexity and the explicit uncertainties are pronounced. Limitation of a physic-economic metric arises from the amount of information required. Simple metrics, however, such as physical ones are indispensable for ensuring operational feasibility. The complexity (e. g. in case of the GDP) might open the way to strategic manipulations and undermine the likelihood of reaching an agreement on metrics (UNFCCC and SBSTA, 2012). Further, the complexity might involve significant transaction costs on the level of implementation.

Discussion

The reflection of a set of normative and policy decisions – be it implicit or explicit – implies, that each simple climate metric has a direct link to pivotal landmark decisions in climate policies. A climate metric reflects the consequences of superordinate policy decision in a compact way. It has the potential to act as a communication tool to develop a joint understanding of the complex climate policy setting among different scientific disciplines and between science, policy- and decision-makers. At the same time, however, the ostensible simplicity of a metric invite policy-makers to apply them without understanding the underlying normative decisions.

In the literature (e.g. Berntsen et al., 2010; Tanaka et al., 2013; Ekholm et al., 2013) it is intensively discussed which metric is most appropriate to reach the 2 °C target. Some scholars argue, that a flaw of the GWP is that it is not designed to guide emissions towards any stabilization target (e.g. the 2 °C target). Chapter 2 highlights the effect from transferring the cost-effectiveness approach to the concept of metrics, which is an inherently marginal concept. In this context, however, the question arises whether the choice of a cost-effective policy approach such as the 2 °C target on the overall policy level justifies to adopt a biased economic damage function (θ_∞ – function) for optimization at the margin. Or the other way around: even in case of the cost-effectiveness approach, there could be strong arguments for considering the benchmark metric GDP (or other simplified cost-benefit metrics) instead of e.g. the GCP. This discussion should be subject to further interdisciplinary climate metric research.

As long as the climate stabilization and mitigation strategy for reaching the 2 °C target is only vaguely defined i.e. an unclear role of the rate of climate change and a lack of binding intermediate targets, there is wide scope for metric design. In the face of ambiguity in current policy objectives Ekholm et al. (2013) suggest identifying metrics that perform well with different relevant problem formulations e.g. different ways to reach the 2 °C target. Such a metric has the potential to be more resilient to possible adjustments in future policy objectives. This pragmatic perspective could pave the road to a politically accepted refined metric concept in line with the 2 °C target.

While this thesis provides conceptual clarity in the discussion on metric design elements, of overriding importance, is also the impact of alternative metrics on short- and long-tern multi-gas emission reductions and the associated economic costs. Substantial cost-efficiency advantages arise from including also the relevant non-CO_2 effects in the mitigation strategy (e.g. van Vuuren et al., 2006; Weyant et al., 2006) , which is facilitated by the availability of a politically accepted metric. The metric design, however, is a secondary, downstream decision. Economic modelling studies (Strefler et al., 2013; Reisinger et al., 2013) show that the metric choice has a relatively small impact on the CO_2 budget compatible with the 2 °C target and on global costs. However, the metric choice affects substantially the regional distribution of costs and could be important for the political economy of regional and sectoral participation in collective mitigation effects, in particular changing costs and gains over time for agriculture and energy-intensive sectors.

6.3 Trading-off SLCF and CO_2 – critical metric design issues (RQ II)

What is the implication of a short atmospheric lifetime for the calculation of climate metrics? What are critical factors for metric design when comparing short- and long-lived climate effects such as aviation-induced contrails and CO_2?

Trading off SLCF and CO_2 is complicated as two perturbations with distinctly different properties with respect to scales of time and space are compared. Moreover, with respect to SLCF, due to spatial and temporal heterogeneity, there is only an approximate relationship between emissions, the emergence of (indirect) SLCF and the climate change induced. The trade-off between simplicity and operational feasibility, a common dilemma in metric design, becomes even more pronounced.

Considering global-mean metrics for SLCF (Chapters 3, 4) means ignoring some structural uncertainty for reasons of operational feasibility, which is a pragmatic forward in metric design. When considering their effect on the level of global–mean radiative forcing, SLCF can be treated in a generic form, due to their short atmospheric lifetime. When trading-off SLCF and CO_2 on the basis of emission-based global–mean metrics, the basic challenges of climate metric design persist, some of the critical design factors reinforce due to the nature of SLCF. The assessments demonstrate that:

1 The level of scientific uncertainty rises. Scientific uncertainties with respect to the emergence and climate response are SLCF-specific and transfer directly into a large bandwidth of metric values for SLCF. They have the potential to critically control the policy outcome. The largest factors of scientific uncertainty (in the considered cases: efficacy, contrail cirrus), however, have a linear scaling effect and thus affect all metrics in similar terms (Chapters 3, 4).

2 The normative value judgements and policy decisions associated with the time frame, the policy framework, the evaluation horizon (Chapter 3) and the time frame parameter (discount rate and time horizon, Chapter 4) substantially affect the relative weighting of SLCF and CO_2. With a change in time frame parameter, CO_2 equivalences for SLCF easily duplicate and the evaluation of a trade-off situation easily switches to an opposite policy recommendation.

3 In certain cases, a critical policy decision for trading-off SLCF and CO_2 is whether a single pulse emission is considered or whether the assumption is taken that the emission situation will continuously repeat in the future (sustained emissions). From an economic perspective, however, pulse based metrics are suited better for policy analysis than sustained emission

metrics can be derived from pulse emission metrics through convolution (see e. g. Boucher, 2012).

In the considered cases the evaluation of SLCF tend to be more sensitive to SLCF specific uncertainties and the relative weighting of impacts along the temporal axis than to the selected metric approach (physical, physico–economic) and thus to damage considerations. Global-mean CO_2 equivalences for SLCF are limitedly robust as they are expected to be subject to a large variability when scientific knowledge on the climate system and particularly the scientific knowledge on small scale climate impact of SLCF advances and the perceived urgency of near-term mitigation mitigation evolves.

The presented metric concepts based on global-mean in- and output figures provide important information for average emission situations on an annual basis e. g. for evaluation of trade-offs when considering fleet movements on average global-mean level (Chapter 3) or life cycle assessments and inventories (Chapter 4). Their assessment reveals critical factors of metric design and serve as starting point for more refined analyses on SLCF. In principle, the concepts could be adjusted to regional small-scale input data. The global-mean effect of an individual perturbation can be evaluated, once scientific knowledge on the climate interaction of SLCF advances, see also the synthesis to RQ III.

Discussion

Policy recommendations with respect to SLCF have a direct link to priorities in the mitigation strategy. They address two central but controversial decisions in climate policies:

- how to address the rate of climate change in the context of long-term climate change and
- the choice of an adequate discount rate to weigh future climate benefits and costs.

As outlined in the introduction, adopting the 2 °C target means avoiding 'dangerous anthropogenic interference in a time frame sufficient to allow ecosystems to adapt naturally to climate change' (UNFCCC, 1992). This implies that climate policies should concern both, limiting the absolute level of climate change and additionally limiting the rate of climate change (e. g. Hansen et al., 2007; Jackson, 2009; Penner et al., 2010; UNEP, 2011; Molina et al., 2009; Borken-Kleefeld et al., 2011).

If long term climate change is in the fore, large time horizons or small discount rates (such as 100 a or 2 %) would be the natural choice, resulting in small metric values for SLCF. However, if there is additionally the goal to limit the current rate of change, a shorter time horizon and higher discount rates (e. g. 50 a or 4 %) are justified. The relative importance of SLCF would turn out to be markedly larger (e. g. Chapter 4).

Incentives for mitigating SLCF can be provided by envisaging short-term targets (cost-effectiveness approach) or considering also near term damages (cost-benefit). The incentives would facilitate to build up scientific knowledge and institutional capacity to slow down the rate of global warming. They become increasingly important as the development of innovative reduction technologies usually requires a time to handle of up to 10 – 20 a e. g. for the development of aircraft and energy infrastructures.

The science based policy decision, how to address the two diverging targets of short- and long-term climate change mitigation, is directly linked to the the normative decision on appropriate discount rates for climate change damages. It is one of the most pivotal, but controversial policy decision in climate policies, which dominates the economic and political discourse on the appropriate mitigation strategy ('Stern - Weitzman debate') (Stern, 2007; Nordhaus, 2007; Beckerman and Hepburn, 2009; Hepburn, 2006).

6.4 Lessons learnt for the aviation sector (RQ III)

How can short-lived climate forcers in aviation such as contrails be traded-off against long-lived CO_2 forcing?

The conceptual challenge of trading off SCLF and CO_2 has been illustrated, using the example of contrails. The core findings, however, can be generalised to any type of SLCF. As outlined in the introduction, the challenge of overriding importance in the aviation sector is to quantify the current and future climate impact of short-lived non-CO_2 perturbations. In this context the assessment provides important insights:

A single, generally accepted contrail metric, respectively a CO_2 equivalence for all aviation-induced non-CO_2 effects cannot be provided. However, for a specific policy questions and defined downstream policy decisions and value judgements, metric assessments can provide quantified estimates (see also Azar and Johansson, 2011; Dorbian et al., 2011):

Under defined reference case conditions[1] we obtain a best estimate for an average-global mean contrail metric of 0.19 (0.13 – 0.32), 3.5 (2.3 – 5.8) kg CO_2e per average flight-km and 1.20 (1.13 – 1.32) kg CO_2e per average kg fuel burn, respectively. The values triple, up to octuplicate, when including contrail cirrus. Considering a higher discount rate ($r = 4\,\%\ a^{-1}$) or a shorter time horizon ($H = 50\,a$) which could also be justified from ethical point of view, the metric value doubles. These values are valid for the given snap-shot of policy priorities and scientific knowledge and are expected to vary over time.

The presented contrail metrics based on global- and annual-mean input figures, however, disguise the variability of the individual climate responses. When and

[1] Point in time of emission release: 2005, RCP2.6, contrail efficacy $E_{SLCF} = 1$, a discount rate $r = 2\,\%$ and a time horizon $H = 100a$).

where the flights occur has a significant impact on the resulting climate impact. For example, according to Dings et al. (2002), contrail formation occurs only in about 10 % of the annual flight duration, and thus, in first approximation, in 10 % of the flight-km. Consequently, the annual RF by contrails is caused only by one tenth of the total flight-km, the activity-based CO_2 equivalence for contrails turns out to be larger by a factor of 10. Contrails occur only in a few flight situations, in which they cause a substantially higher impact than is reflected by the average global–mean metric. Roughly, climate impact is largely overestimated in 90 % of the flight duration, and strongly underestimated in 10 % of flight duration. Additionally, the climate response of an individual flight situation with contrails is influenced by a number of external physical and chemical factors: i. e. night flights have a stronger warming effect than daytime flights and winter flights may warm the surface more than summer flights (e. g. Stuber et al., 2006).

In the EU project REACT4C[2] the feasibility is explored of adopting flight altitudes and flight routes that lead to reduced fuel consumption and emissions, and lessen the environmental impact. Research is undertaken to advance the understanding of the complex interrelation between aerosols, cloud formation and contrail cirrus. For example, the European Centre for Medium-Range Weather Forecasts has implemented a tool for the predication of of ice-supersaturated areas by weather forecast. A sound evaluation of the results will be performed (personal communication with K. Gierens, DLR Nov. 2013). Currently, however, climate science is not yet elaborated enough to provide appropriate guidance in an individual perturbation situation involving contrails and CO_2 or to serve as basis for market-based instruments. Future research is needed.

Discussion

Including non–CO_2 effects in the future aviation mitigation strategy promise substantial cost-efficiency advantages. Alternative mitigation options, which are expected to be moderate in costs, could become available and potential trade-offs could be considered in future developments (e. g. aircrafts). In contrast, we learn, in line with Forster et al. (2007), that scientific findings are still not fair enough for evaluating an individual contrail situation, i. e. likewise for designing policy instruments, that directly provide incentives in an individual emission situations (e. g. emission trading, prices). In spite of the presence of normative, scientific, scenario and structural uncertainty, policy-maker should set the course for contrail mitigation when providing guidelines for technology development. In line with scientific findings on the appropriate metric (GWP) in the context of a multi-gas strategy (van Vuuren et al., 2006): For cost-efficient mitigation, it is more important to include non-CO_2 effects rather than to define an exact metric value.

[2]Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate. Project in the Seventh Framework Programme of the European Commission, www.react4c.eu

6.5 Outlook

Limiting not only long-term climate change, but also controlling the rate of climate change are considered as key challenges in the future climate policy framework. In a climate regime with two climate targets of equal, but diverging policy priority a multi-gas strategy with a single metric value for all types of climate responses comes to its limit. Metrics and CO_2 equivalences for SLCF treat SLCF and CO_2 as substitutes ('either' decision). However, with advancing climate change, complementary action on SLCF and CO_2 is required.

An option for pursuing the two opposing priorities, transferring this 'both and' – decision to the policy framework is to decouple short- and long-term effects by establishing/employing a second basket for SLCF (Fuglestvedt et al., 2000; Rypdal et al., 2005; Daniel et al., 2012; Smith et al., 2012). Such a two-pronged institutional framework could be convenient for policy design and implementation, whereas the importance of long-term climate stabilization is clear, the perceived urgency of near-term mitigation will evolve with our knowledge of the climate system. It provides the opportunity to regulate SLCF separately and to dynamically adjust the pace of near- and long-term mitigation efforts. Such flexibility would allow new scientific knowledge and revisions of climate policy targets in the future to be incorporated into the metric for SLCF.

In a multitude of policy application, global–mean metric approaches are well-suited for comparing long-lived GHG, however, for trading off SLCF and CO_2 it is important to consider the individual atmospheric conditions. Science should focus on reducing uncertainties in non-CO_2 climate impact estimates and the policy task is to set the course for SLCF mitigation e. g. by providing guidelines for technological development of infrastructure. The expected trend according to the current scientific knowledge – increasing importance of SLCF when limiting the rate of change becomes more prioritised – should be clearly communicated so that stakeholders are in a position to prepare.

Chapter 7

Statement of contribution

The core chapters of this thesis (Chapter 2 – 5) are the result of the co–operation between the author of this thesis and her advisers Dr. Gunnar Luderer and Prof. Dr. Ottmar Edenhofer (Potsdam Institute for Climate Impact Research, PIK) and Prof. Dr. Robert Sausen (Deutsches Zentrum für Luft- und Raumfahrt, DLR). The author of this thesis has developed the conceptional design of the PhD project on her own. The author made extensive contributions to the contents of all four papers, from conceptual design and technical development to writing. This section acknowledges major contribution of others.

Chapter 2: The conceptual design, the technical development and the writing was in close co-operation by the author and Dr. Gunnar Luderer, with revisions by Prof. Edenhofer. The author developed the original idea, was responsible for the literature review and for writing the article. Dr. Gunnar Luderer contributed substantially in clarifying central aspects and in refining the conceptual framework. He made important contributions to the presentation and discussion of the results and encouraged revisions following the reviews of the first draft. Prof. Ottmar Edenhofer gave due support and contributed in discussions.

Chapter 3: The author conceived the idea for this research. The concept of the metric-based evaluation framework was then jointly developed by the author in co-operation with the co-authors at the DLR (Prof. Robert Sausen, Dr. Sigrun Matthes, Dr. Michael Ponater). The author implemented the numerical assessment, elaborated the more specific research question and was responsible for the subsequent analysis and visualization of results. The co-authors at DLR provided important input and feedback to early drafts of the article and had a watchful eye on the details and formalities. The article was written by the author while the co-authors at DLR reviewed it critically.

Chapter 4: The author developed the research question and the numerical assessment for this chapter. Dr. Gunnar conceived the generic formulation of SLCF climate metrics. Interpretation and discussion was undertaken in co–operation with Dr. Gunnar Luderer and Prof Robert Sausen. They made substantial contributions in structuring the argument and in conceptualizing the results. The article text was written by the author with important revisions by Dr. Gunnar Luderer and Prof. Robert Sausen.

Chapter 5: The author was solely responsible for the conceptual design and writing of the article. Dr. Martin Cames by the Öko Institut provided helpful comments.

The linear response model LinClim which was applied to perform the analysis was kindly made available by Dr. Ling Lim and Prof. David Lee (Centre for Aviation Transport and Environment (CATE), Manchester Metropolitan University (MMU), United Kingdom).

Chapter 8

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Appendix A

Supplementary material

A.1 Chapter 3

$$GWP(H)_i = \frac{\int_0^H RF_i(t)dt}{\int RF_{CO_2}(t)dt} = \frac{\int_0^H a_i c_i(t)dt}{a_{CO_2} c_{CO_2}(t)dt} = \frac{AGWP(H)_i}{AGWP(H)_{CO_2}} \tag{A.1}$$

The Global Warming Potential (GWP) (Eq. A.1) represents the integrated RF caused by a pulse emission over a chosen time horizon H relative to that of the reference gas CO_2 where RF_i is the global mean RF of component i; a_i is the RF per unit mass increase in atmospheric abundance of component i (radiative efficiency); and c_i is the atmospheric concentration of component i

$$MGTP(H)_i = \frac{\int_0^H \Delta T_i(t)dt}{\int_0^H \Delta T_{CO_2}(t)dt} = \frac{MGTP(H)_i}{MGTP(H)_{CO_2}} \tag{A.2}$$

The Mean Global Temperature Potential (Eq. A.2) provides the average-mean temperature response caused by a pulse emission over a chosen time horizon H relative to that of the reference gas CO_2, assuming constant atmospheric conditions.

$$GTP_p(H)_i = \frac{\Delta T_i^H}{\Delta T_{CO_2}^H} = \frac{AGTP_{p,i}^H}{AGTP_{p_{CO_2}}^H} \tag{A.3}$$

The Global Temperature (Change) Potential (GTP_p) (Eq. A.3) describes the the global mean sur-face temperature change after a fixed time horizon of H years following an (pulse) emission of compound i relative to that of CO_2. Our standard metric assumes constant atmospheric conditions.

The time-dependent version in the context of a specific climate target $GTP_p(t)$ calculates the Global Temperature (Change) Potential each year between a starting year t_0 and a target year

t_{tar} by taking into account a specific stabilisation pathway. The target year t_{tar} is defined as time at which, along this specific stabilisation pathway, a climate target is expected to be reached, see for more methodological details Shine et al. (2007).

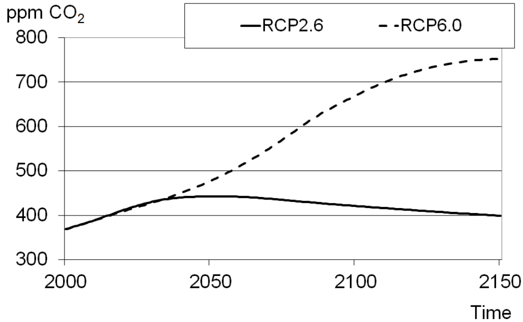

Figure A.1: *Atmospheric CO_2 concentration of the Representative Concentration Pathway RCP2.6 where RF peaks at a value of around 3.1 $W m^{-2}$ for mid-century and declines to 2.6 $W m^{-2}$ by 2100 and of RCP6.0 for which total RF is stabilized at approximately 6.0 $W m^{-2}$ after 2100 without overshoot.*

Aviation emission type	**Impact function** Proxy	Background (*ref*)	**Weighting function** Physical cost-benefit metric $M_{cba}(t)$ average-mean $\theta(H,t); H = const$	end point $\delta(t_x,t); t_x = const$	Physical cost-effective metric $M_{ce}(t)$ average-mean $\theta(H,t); H = D^{tar}$	end point $\delta(t_x,t); t_x = t_{tar}$
pulse	ΔT	constant	$MGTP_p^{const} = \underline{MGTP}$	$GTP_p^{const} = \underline{GTP_p}$		
pulse	ΔT	scenario	$MGTP_p^{scen}$	GTP_p^{scen}	$MGTP_p^{const}$	$GTP_p^{scen} = \underline{GTP_p(t)}$
sustain	ΔT	scenario	$MGTP_p^{scen}$	GTP_p^{scen}	$MGTP_p^{const}$	GTP_p^{scen}
sustain	ΔT	scenario	$MGTP_p^{scen}$	GTP_p^{scen}	$MGTP_p^{const}$	GTP_p^{scen}
scenario	ΔT	scenario	$MGTP_p^{scen}$	GTP_p^{scen}	$MGTP_p^{const}$	GTP_p^{scen}
pulse	*RF*	constant	$GWP_p^{const} = \underline{GWP}$			
pulse	*RF*	scenario	GWP_p^{scen}		GWP_p^{scen}	
sustain	*RF*	constant	GWP_s^{const}			
sustain	*RF*	scenario	GWP_s^{scen}			
scenario	*RF*	constant	GWP_{scen}^{const}			

Table A.1: *Specification of applied metric types (standard metrics underlined) according to the aviation emission type, impact function (proxy for climate impacts and future atmospheric conditions) and weighting function (based on Deuber et al., 2013a) The underlying end point and average mean weighting functions, the unit step function $\theta(t)$ and Dirac Delta function $\delta(t)$, are specified in Eq. 2.2 and 2.3, p. 22.*

A.2 Chapter 4

The discounting weighting function is defined as

$$W_D(t) \;=\; r \cdot e^{-rt}, \tag{A.4}$$

where r is the discount rate.

The Global Warming Potential for short-lived climate forcers (SLCF). The Global Warming Potential and the Mean Global Temperature Potential (Eq. A.5 and A.6) are here defined relative to the reference system at the point in time of emission release (constant atmospheric conditions), as often done in the framework of physical metrics (e. g. Forster et al., 2007).

$$GWP(H) = \frac{AGWP_{\mathrm{SLCF}}}{AGWP_{\mathrm{CO_2}}} = \frac{1/\epsilon_{\mathrm{SLCF}} \int\limits_{t=t_0}^{\infty} (RF_{ref(t_0)+SLCF}(t) - (RF_{ref(t_0)}(t)) \cdot W(t)dt}{1/\, RF_{\mathrm{SLCF}} \int\limits_{t=t_0}^{\infty} 1/\, RF_{\mathrm{SLCF}}(RF_{ref(t_0)+EM_{\mathrm{CO_2}}}(t) -\, RF_{ref(t_0)}(t)) \cdot W(t)dt} \tag{A.5}$$

Here ϵ_{SLCF} is a proxy for the SLCF, i.e. the $\mathrm{RF_{SLCF}}$ integrated over one year [unit: mW $\mathrm{m^{-2}}$a] or a measure of activity (e. g. in case of contrails: length of flight trajectories [unit:km], mass of fuel burned [unit: kg]).

$$MGTP(H) = \frac{AMGTP_{\mathrm{SLCF}}}{AMGTP_{\mathrm{CO_2}}} = \frac{1/\epsilon_{\mathrm{SLCF}} \int\limits_{t=t_0}^{\infty} (\Delta T(RF_{ref(t_0)+SLCF}(t)) - \Delta T(RF_{ref(t_0)}(t)) \cdot W(t)dt}{1/\, RF_{\mathrm{SLCF}} \int\limits_{t=t_0}^{\infty} (\Delta T(\Delta C_{ref(t_0)+EM_{\mathrm{CO_2}}}(t)) - \Delta T(\Delta C_{ref(t_0)}(t)) \cdot W(t)dt} \tag{A.6}$$

The unit step function (no discounting) is defined as

$$W(t) = \frac{1}{H} \cdot \theta(H-t) = \begin{cases} 1/H & for\ t \quad \leq \quad H \\ 0 & for\ t \quad > \quad H \end{cases} \tag{A.7}$$

where H is the time horizon.

0^{th} moment of the weighting function is defined as

$$\int\limits_{0}^{\infty} W_i(t)\, dt \;=\; 1. \tag{A.8}$$

It follows for the discounting weighting function:

$$W_D(t) \;=\; r\; \cdot e^{-rt} \tag{A.9}$$

and for the unit step function:

$$W_{USF}(t) \;=\; \frac{1}{H}\theta(H-t) \tag{A.10}$$

1^{st} moment of the weighting function. For $r = 2/H$ follows for the discounting weighting function (Eq.A.2) and the unit step function (Eq.A.5):

$$\int_0^\infty W_D(t)\,dt = \int_0^\infty W_{USF}(t)\,dt \tag{A.11}$$

The two weighting functions, the discounting function (Eq. A.2) and the unit step function (Eq. A.5) are not identical by definition. However, we argue that they can be considered comparable if the discount rate r (in a^{-1}) is twice the inverse of the time horizon H (in a), since under this condition the respective 0^{th} moment (normalised function to 1, Eq. A.8) and the 1^{st} moment (expectation values of distribution, Eq. A.2) are equal.

	Reference case	**Sensitivity case**
Point in time of emission release	2005	2050, 2100
corresponding CO_2 conc. level	379 ppmv	443, 420 ppmv
Reference concentration pathway	RCP2.6	RCP6.0
	(Van Vuuren et al., 2011)	(Masui et al., 2011)
Time frame parameter	$r = 2\ \%\,a^{-1}$	$r = 0.4\ \%\,a^{-1}$, $= 4\ \%\,a^{-1}$
	$H = 100a$	$H = 500\,a$; $H = 50\,a$
Climate characteristics	$\tau = 37.4\,a$	$\tau = 10$ and $50\,a$
	$\lambda = 0.64\ K/Wam^{-2}$	

Table A.2: *Input parameter for the reference case assumptions and sensitivity studies*

Type	Unit	Metric M						
		GDP			GWP(H)	$GWP_d(r)$	MGTP(H)	$MGTP_d(r)$
		n = 1	n = 3	n = 5				
EQ_M	Tg_{CO_2e} $(mW\,m^{-2}\,a)^{-1}$	19.6	12.0	8.2	9.6	17.9	12.7	17.9
EQ_M^A	kg_{CO_2e} $(km)^{-1}$	5.8	3.5	2.3	2.9	5.2	3.8	5.2
EQ_M^{FFE}	kg_{CO_2e} $(kg\,CO_2)^{-1}$	0.32	0.19	0.13	0.16	0.29	0.21	0.29

Table A.3: *Forcing-based, activity-based and fossil-fuel-based CO_2 equivalence factors (EQ_M, EQ_M^A and EQ_M^{FFE}) to derive CO_2 equivalences for contrails as function of metric choice.*

		ref	$r = 4\,\%a^{-1}$	$r = 0.4\,\%a^{-1}$	RCP6.0	$\tau = 50a$	$\tau = 10a$	$T_{EM} = 2050$	$T_{EM} = 2100$
EQ_{GDP}	$n = 1$	19.57	32.83	6.22	21.30	19.57	19.57	20.19	19.14
Tg_{CO_2e} $(mW\,m^{-2}\,a)^{-1}$	$n = 3$	11.96	21.04	4.89	8.71	11.85	11.90	19.37	21.66
	$n = 5$	8.16	13.91	4.08	3.44	7.19	8.26	18.53	23.97
$AGDP_{CO_2}$	$n = 1$	1.92	0.81	9.10	1.76	2.90	1.67	1.86	1.96
$1/10^{14}\ kg_{CO_2}\ a^{-1}$	$n = 3$	8.2	2.77	37.00	13.03	17.43	6.24	10.64	10.42
	$n = 5$	22.11	6.28	99.16	105.78	62.90	15.00	34.29	31.59
$AGDP_{SLCF}$	$n = 1$	0.38	0.27	0.57	0.38	0.57	0.33	0.38	0.38
$1/(W\,m^{-2})^{-1}$	$n = 3$	0.98	0.58	1.81	1.13	2.07	0.74	2.06	2.26
	$n = 5$	1.81	0.87	4.05	3.64	4.52	1.24	6.35	7.57

Table A.4: *Economic forcing-based CO_2 equivalence factors (EQ_{GDP}) and underlying absolute factor values ($AGDP_{CO_2}$, $AGDP_{SLCF}$) for $n = 1$, $n = 3$ and $n = 5$ in the reference case (ref) and sensitivity to selected input parameters (background concentration pathway RCP6.0, discount rate $r = 4\,\%\ a^{-1}$, $r = 0.4\,\%\ a^{-1}$, climate response time $\tau = 10a$, $\tau = 50a$, point in time of emission release T_{EM} = 2050 and 2100).*