Climate forcing of aviation emissions in high altitudes and comparison of metrics

An update according to the Fourth Assessment Report, IPCC 2007
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Abstract

Based on the 4th Assessment Report of the IPCC released in 2007, this paper assesses the actual range of the Radiative Forcing Index (RFI), discusses its relevance in comparison to the Emission Weighting Factor (EWF) that is similar to the Global Warming Potential (GWP) and tests the hypothesis, according to which CO_2 emissions from aviation enhance global warming to a larger extent than the non-CO_2 impacts in the long term. The RFI is calculated with a range of 1.9 - 4.7. A "best guess" estimate is not given, in contrast to the 1999 IPCC Report. The EWF, calculated with a time horizon of 100 years, has the same order of magnitude, but is altogether smaller than the RFI (1.2 – 2.7). Thus, the warming effect of non-CO_2 emissions of aviation (e.g. ozone formation, aviation induced cloudiness) can be either larger or smaller than the warming effect of CO_2 emissions over this time horizon. The comparison of the two metrics shows the ongoing validity of the original rationale of the IPCC for the RFI. During the chosen time horizon, the EWF has a delay in reflecting the actual radiative forcing and thus underestimates the climate impact in this phase. The EWF only starts to catch up on the RFI when aviation emissions decrease. With respect to climate policies, the RFI may be more meaningful, because it better reflects the climate forcing of aviation for the relevant coming decades than the EWF. Based on radiative forcing, the aviation contribution to global warming amounts to about 2% from CO_2 emissions, and about 3 – 7% for the combined aviation effects. Put into larger context of defining policy issues, both metrics can be used for environmental policy making.

1. Introduction

Since the late 1980's the climate impact of air traffic is subject to international research (e.g. Schumann et al., 1991). One of the research areas is the assessment of climate forcing of air traffic emissions in high altitudes from 9 to 12 km. IPCC's 4th Assessment Report from 2007 also presents the results for different aviation climate impacts, such as ozone formation and aviation induced cloudiness. In summary, aviation causes a larger radiative forcing (RF) than from CO_2 emissions alone (IPCC 2007, WGIII, Chapter 5).

In this paper we will discuss three metrics, the GWP, the RFI and the EWF and compare CO_2 and non-CO_2-emissions from aviation. Whereas the GWP is the most widely used metric for long-lived gases, the RFI and EWF have been specifically developed for aviation. Based on the IPCC Report from 2007, this paper assesses the current range of the RFI, discusses its relevance in comparison to the GWP-similar EWF and tests the statement, according to which the CO_2 emissions from aviation warm the global climate in the long term to a larger extent than the non-CO_2 emissions.

2. Aviation Metrics

Metrics are used for the comparison of the warming effects of different greenhouse gases. They usually compare the emissions or warming impacts of a given amount of emissions or their impacts to those of a certain amount of CO_2 emissions, that would have an equivalent warming effect.

2.1 Global warming potential (GWP)

The so-called Global Warming Potential (GWP) is an emission metric: A given quantity of emissions of a given gas can be multiplied with the constant GWP to result in an amount of CO_2 emissions that has an equivalent radiative forcing over a chosen time horizon (CO_2-equivalent emissions). The GWP has been designed for long-lived greenhouse gases (GHG) (atmospheric life times of decades and more). Technically, the GWP integrates the radiative forcing produced by a given mass of a given gas after its

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pulse emission over a chosen time horizon and compares this to an equal mass of CO_2 emissions. Thus, the atmospheric life time of the gas influences the assessment of its climate forcing. In the context of the United Nations Framework Convention on Climate Change (UNFCCC), countries agreed on a time horizon of 100 years after the pulse emission.

The GWP continues to be the main metric applied in international climate policies. Alternative metrics are currently discussed but not recommended by the IPCC (IPCC 2007 I, Chapter 2.10). The IPCC recommends the GWP, however, for long-lived GHGs only.

2.2 Radiative Forcing Index

In the case of aviation, where non-CO_2 effects like ozone formation and cloudiness are short-lived, the GWP offers no meaningful approach (IPCC 1999). Hence, the IPCC established the RFI (Radiative Forcing Index) as metric for aviation in 1999. The RFI is a simple ratio of the RF of the non-CO_2 effects of aviation at a given point of time and the RF of the aviation CO_2-emissions, accumulated since 1950 (IPCC 1999). For the year 1992 the overall RFI has been determined to be in the range of 2-4 (IPCC 1999). The overall RFI can be split into specific RFIs for different aviation effects, e.g. for condensation trails or for ozone formation.

While the GWP is an emission metric, the RFI is an "impact" metric, where we see the RF as first order impact. Its numeric value defines the ratio of the RFs of certain agents (such as NO_x, causing ozone formation, and CO_2) rather than comparing emission quantities. Therefore, for a given pollutant it does not deliver "CO_2-equivalent emissions", as the GWP does, but rather "CO_2 emissions that would have the same RF", considering the history of aviation. Taking the first order impact rather than the emission perspective, the RFI does not account of the complex non-linear dependencies between e.g. the quantity of soot emissions and their residence time, or flight altitude and contrail formation. The RFI rather acknowledges that soot and other emissions may be part of a triggering process for e.g. contrails. Since the relation between the quantity and residence time of soot and the final contrail is not linear and depends on a host of other parameters, the RFI does not attempt to find a linear conversion factor between soot and contrails, but leaves out soot as such entirely and progresses directly to the average RF of contrails. The different residence times are considered by the RFI. A RFI calculated e.g. for the year 2005 counts the RF of CO_2 emitted by aviation in 1970, taking into account the part of the CO_2 emitted in 1970 that has left the atmosphere until 2005. In the same manner, condensation trails produced by aviation in 1970 are included in the RFI of 2005, since the RFI acknowledges that these contrails have disappeared within a few hours after formation, and thus takes the 2005 RF of 1970 contrails as zero. Therefore the RFI has a "built in" time horizon, since it counts the globally averaged RF impacts of all aviation emissions since 1950. Hence, the RFI reflects the history up to the present of all aviation influences on the radiation budget. For the short-lived and complex non-CO_2-effects of aviation this appears to be more adequate, since "the history of radiative forcing, calculated for the changing atmosphere, is a far better index of anthropogenic climate change from different gases and aerosols than is GWP" (IPCC 1999, Chapter 6.2.2.).

The RFI is often used as a factor, cited within the above range of 2-4, that has to be multiplied with the pure CO_2 effect in order to get the overall warming effect of aviation (e.g. Deutscher Bundestag 2002, Department for Transportation 2004). Critics of the RFI point out that such factors, perceived as constant, are not adequate, since in reality they would be time dependent. Taking life time into account, CO_2 would in the long term warm the climate stronger than the non-CO_2 effects (Schumann 2007). As we have discussed above, this needs closer examination, using the most recent numbers available.

2.3 The EWF (Emission Weighting Factor)

In order to illustrate the time dependency of the different aviation effects Forster et al. (2006) developed the so called EWF (Emission Weighting Factor). Similar to the GWP, the EWF compares the integrals over the radiative forcing of the CO_2 and non-CO_2 effects of aviation during a chosen time horizon, after the emission pulse. In short, the EWF is like a GWP for aviation, but is based on impacts rather than emissions. Contrary to the RFI, the EWF looks into the future development of the radiative forcing over a chosen time, resulting from the emission pulse.

2.4 Other metrics

For all metrics discussed above, the variables used are gases, emission quantities, their radiative forcings and time horizons. Some metrics have been proposed using more variables, such as the Global Temperature Potential (GTP). The GTP measures the warming effect of a gas based on the temperature increase it causes on the earth surface, over a given time horizon. However, it has been shown that on the time horizon of 100 years, politically agreed for the GWP, the GTP delivers results close to the GWP and therefore does not offer a much different assessment of the warming impact of the gases. To date, no metric applied in practice includes other parameters which might be politically desirable (such as damage costs or benefits, discount factors, regional differentiation, etc.).

3. The calculation of the RFI and the EWF

The Fourth Report of IPCC 2007 discusses aviation in Working Group I (Chapter 2.6) and III (Chapter 5). This paper will quote these sources as IPCC (2007). The IPCC expresses the aviation effects as radiative forcings (RF) including the summarising term 'AIC' (aviation induced cloudiness) for the effects of aviation on clouds like linear contrails and cirrus clouds induced by aviation. On this basis, we directly calculate the RFI and EWF, using the RF values of IPCC (2007) and applying them to the formulae for both metrics. Results are shown in table 1:

- Lines 1-6 reflect the RFs from IPCC (2007). Line 2 shows the combined effect of H_2O, sulphate and soot particles. Line 3 combines ozone formation and methane. The value in line 5 is bracketed because IPCC does not offer a best estimate for AIC and itself puts the value in brackets.
- The lines 7-9 show the RFI values calculated according to IPCC (1999). Due to the lacking best estimate for AIC RF the value in line 8 is again bracketed.
- Line 10-14 show the values of the absolute global warming potentials (AGWP). These are calculated with the method of Forster et al. (2006), directly from the RF values given in line 1-6. The values in line 11-12 are quoted directly from Forster et al. (2006), because these were already based on the RF values from the later IPCC (2007). Line 13-14 use the same method and the new values from IPCC 2007 for AIC, with the above mentioned reservations regarding the “mean” value for AIC. The AIC-values do not change with the time horizon, because the time integral for shot-lived cloud effects does not change after the first few days.
- The lines 15-17 show EWFs on the basis of the AGWPs from line 10-14.

Table 1: RFI based on IPCC (2007) and AGWP. EWF given for comparison.

Line	Source		Units	RF in 2000				
1	I (1)	RF CO_2 (accumulated since 1950)	mW/m^2	25				
2	I (3)	RF net H_2O, sulphate and soot particles	mW/m^2	1				
3	I (3)	RF net CH_4 and O_3	mW/m^2	12				
4	I (1)	RF AIC*, lower bound	mW/m^2	10				
5	I (1)	RF AIC, "mean"	mW/m^2	(30)				
6	I (1)	RF AIC, upper bound	mW/m^2	80				
7	B	RFI***, incl. AIC, lower bound	RFI	1,9				
8	B	RFI, incl. AIC, "mean"	RFI	(2,7)				
9	B	RFI, incl. AIC, upper bound	RFI	4,7				
		Time horizon (start 2000)	years		1	20	100	500
10	I (1)	AGWP CO_2	$10^{-14} Wm^{-2}$ kg CO_2 $^{-1}$ year		0,25**	2,47	8,69	28,6
11	F	AGWP net CH_4 and O_3	$10^{-14} Wm^{-2}$ kg CO_2 $^{-1}$ year		2	0,34	-0,038	-0,038
12	F	AGWP, incl. AIC lower bound	$10^{-14} Wm^{-2}$ kg CO_2 $^{-1}$ year		1,8	1,8	1,8	1,8
13	B	AGWP, incl. AIC "mean"	$10^{-14} Wm^{-2}$ kg CO_2 $^{-1}$ year		(5,5)	(5,5)	(5,5)	(5,5)
14	B	AGWP, incl. AIC, upper bound	$10^{-14} Wm^{-2}$ kg CO_2 $^{-1}$ year		15	15	15	15
15	B	EWF****, with AIC lower bound	[ ]		16	1,9	1,2	1,1
16	B	EWF, with AIC "mean"	[ ]		(31)	(3)	(1,6)	(1,2)
17	B	EWF, with AIC upper bound	[ ]		67	7	2,7	1,5

Sources		
	I	IPCC (2007). I(1) = Working Group I, I(3) = Working Group III
	F	Forster et al., 2006 + Corrigendum published in 2007
	B	This paper, derived from I and F

* AIC = "aviation induced clouds" include linear contrails and cirrus clouds
** Source: Forster et al. (2006)
*** RFI = (RF CO_2 + RF Non-CO_2) / RF CO_2
**** EWF = (AGWP CO_2 + AGWP Non-CO_2) / AGWP CO_2.

4. Results

The RFI amounts to 1.9 - 4.7 according to the updated IPCC (2007) RF values, compared to 2-4 in the previous estimate (IPCC 1999). Thus, the upper bound has risen while the lower bound remained almost the same. The biggest part of the RFI comes from the AIC, for which the IPCC offers only low level of scientific understanding and no best estimate. A best estimate is therefore also not given in this paper.

The EWF ranges from 1.2 – 2.7 at a time horizon of 100 years. Hence, the EWF shows lower numbers than the RFI, with the upper limit being similar to the former best estimate of the RFI (IPCC 1999). Both metrics show the same order of magnitude, although they differ structurally. On first sight, one could presume that the EWF would be several orders of magnitude smaller than the RFI, since its time horizon of 100 years covers most of the life time of CO_2, whereas AIC has only residence times of hours to days. However, the RFI implicitly computes a time horizon of one year for the short term effects like contrails and ozone formation. This is due to the fact that the IPCC bases its calculation on the kerosene consumption of aviation of one year. The corresponding annual aviation emissions cause e.g. an average global coverage of contrails in the climate models, which lasts one year, consisting of continuously appearing and disappearing clouds. Since furthermore the RFI takes into account the CO_2 emissions of aviation since 1950, the RF time horizons of the RFI are not so different from the 100 year for EWF. Broadly, one could say that the RFI is similar to an EWF with a time horizon of some 50 years. We will discuss these similarities in the next section and show that indeed the RFI and GWP may converge to the same values.

Considering the effect of a single flight, the average instantaneous radiative effect of contrails alone is higher by a factor of about 10^4 than the one of CO_2 (see table 1 and shorten the time horizon in line 10 and 12 from one year to one day). The additional greenhouse effect caused by clouds through aviation is so strong that the warming effect according to the upper bound estimations would be larger than the CO_2 contribution (table 1, line 10 and 14), even if integrated over a time horizon of 100 years.

Finally, we relate the sum of the RFs in table 1, lines 1-6, to the entire RF of all anthropogenic activities (1,6 W/m^2, IPCC 2007, WG I). This reveals an aviation share of total global radiative forcing of almost 2% for CO_2 alone and 3-7% including non-CO_2 effects.

5. Time dependencies of the RFI and the EWF

Figure 1 illustrates the time evolution of the RFI and the EWF. It is assumed that air traffic starts in year 1 and constantly produces CO_2 and other emissions until year 201. In year 201, aviation emissions decline to 0 and remain so until the year 300. At five different points A, B, C, D and E the EWF (time horizon 100 years) and RFI values are calculated. Radiative forcing from CO_2 stops rising in year 100, since we cut off the CO_2 100 years after its emission for both metrics. The EWF remains the same at all points since it compares single pulses of CO_2 and non-CO_2 emissions at a fixed time horizon. In contrast, the RFI changes during the first 100 years and afterwards in years 201. During the first 100 years the RFI approaches the EWF value from above and reaches it in year 100. In year 201 (point E) the RFI falls from 2 to 1 (and thus below the EWF).

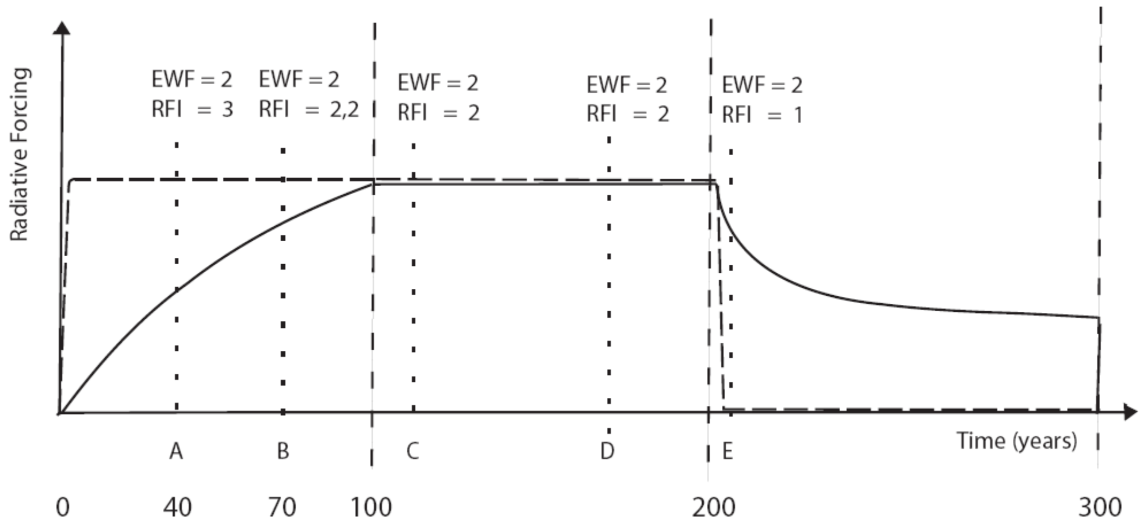

Figure 1: Radiative forcing as a function of time for CO_2 (full line) and the indirect effects of aviation (AIC, O_3, CH_4 etc., dashed line). Emissions start in year 1, remain constant for 200 years and end in year 201. The numerical values are chosen illustratively as an example for an EWF of 2. CO_2 pulses are cut after a time horizon of 100 years, in analogy to the GWP. Furthermore, RFI values are given at certain points in time.

The comparison shows that at constant emissions the RFI stabilizes in the long-term (with the EWF time horizon) at the EWF level, declining from higher values. From that point (in the example year 100) both metrics are identical in their assessment of the emissions. However, before this stabilization only the RFI correctly illustrates the higher forcing due to non-CO_2 effects (corresponding to the area under the dashed line in year 0 to 100), while the EWF underestimates the integrated RF of the non-CO_2 effects (corresponding to only the area below the full curve from year 0 to 100). The difference between the metrics is larger in the beginning and decreases during the first 100 years. These observations do not depend on the particular EWF value (2 in this example) and time horizon (100 years in this example).

Stated differently, the EWF produces a delay in the illustration of the total climate effect during the first 100 years, which are only balanced later when the emissions decrease (in year 201 in this example).

However, the coming decades are particularly important to avoid dangerous climate change. Tipping points in the climate system, like the full meltdown of the Greenland ice sheet, may be initiated at warming thresholds above 1.5° C compared to pre-ind ustrial levels and have the potential to significantly accelerate climate change through feedback effects (see e.g. IPCC 2007, Schellnhuber 2006 and Hansen 2007).

The observations are also valid for increasing or decreasing emissions. With increasing (decreasing) emissions the RFI continuously stays above (below) the EWF. In the case that e.g. air traffic decreases from year 40 in figure 1 and reaches 0 in year 100, the RFI would reach a value of 2 (and thus the EWF value) already in year 70. Thus, the point in time where RFI and EWF match is only shifted for- or backwards through increasing or decreasing emissions. This does however not affect the general delay of the EWF as compared to the RFI.

With regard to climate policies, the first half of the 21st century may be crucial. Only if the industrialised countries reduce their emissions by at least 80% by 2050, a temperature increase of more than 2℃ can probably be avoided. To achieve t his goal, change of energy infrastructure has to take place within the next 10 to 20 years (WBGU 2003). Against this background, the RFI is the more meaningful metric for climate policy, since it expresses the total atmospheric effect of aviation (RF), close to real time.

While it is a peculiarity of the RFI to change systematically over the coming decades, all other metrics are also likely to change their values, due to scientific progress. GWPs have been adjusted continuously since 1991 (see the comparative table actual vs. old GWPs in IPCC 2007, Technical Summary). Further changes to the EWF would become necessary since for example contrails do not only depend on fuel consumption, but also on engine efficiency and routing (IPCC 1999).

6. Climate policy and metric choice

All metrics have the objective to weight different gases in order to help policy makers designing climate policies. Due to this role of metrics as interface between policy and science, the climate effects of different emissions automatically also concern the metrics used.

When assessing the harmfulness of a certain aviation pollutant, the enhanced greenhouse effect is not the end of the story. Since the ultimate aim of climate policy as laid down in the UNFCCC is to stabilize greenhouse gas concentrations at levels that prevent dangerous anthropogenic interference with the climate system, there are more issues that may come into play, such as:

- Inhomogeneous regional distribution of AIC, e.g. the higher probability for AIC formation in high latitudes, where some tipping points may be reached faster.
- Discount factors over different time periods.
- Abatement costs as compared to damage costs.
- National resource endowments (e.g. the role of tourism for a country).
- Value issues such as luxury emissions versus basic emissions (emissions from tourist flights might be perceived different compared to emissions from agriculture).

In this list, which could be extended, the nature of the argument goes from scientific at the beginning towards value and ethical issues at the end. The first item (regional effects of AIC) could be incorporated scientifically into one of the existing metrics (RFI and EWF) to some extent, however, this would require some assumptions on which weight should be given to singular effects such as e.g. the sea level rise due to melting Greenland ice. As for the second item (discount factors), this comes from economic science. The warming and thus damages occurring in 100 years from pollutants emitted today need to be discounted in economic theory, since damages in the future cost less than the same damages occurring today. Since the EWF lags the RFI, this means that from a discounting perspective the EWF downplays the damage of aviation compared to the RFI.

When going further down the above list, increasingly the scientific realm is left and moral and value judgements gain weight, which become more difficult or even impossible to quantify. Ideally, all of these items are somehow recognised and taken into account by policy makers, ultimately mixing scientific knowledge with value judgements. However, there will very likely never be one final metric that incorporates all these factors, since some of them may be largely unknown or not-convertible into quantitative metrics, other may be fully unknown today. For this reason, every science that is available helps to shed light on the issue, but will necessarily be incomplete for policy makers.

However, even within the well known scientific realm, some issues outside the physics may be more decisive than the physics itself. If one assumes a lag of 50 years of the 100 year EWF over the RFI and also assumes a discount factor of 3% (which is the lower bound of discount factors frequently applied by economists to the US economy (Ackerman, 2006), this amounts to a difference of factor 4 over not discounting. While discounting is much debated in economic science, this shows that the economic issue at stake may exceed the physical difference between the RFI and 100 year EWF (roughly a factor of 2).

From an economic point of view, welfare is optimised by including external costs into the prices of goods (c.f. ECMT, 1998). The better the external costs are known, the more policy makers can adapt their strategy to strive for measures bringing about the optimal welfare. Even an estimate of a metric would thus allow to come closer to the optimum than leaving out the metric altogether. It might be for this reason that in many fields of environmental policy the precautionary principle has been introduced, such as the Cartagena Protocol on Biosafety. The European Commission notes on the Precautionary Principle (EC, 2000): "The precautionary principle applies where scientific evidence is insufficient, inconclusive or uncertain and preliminary scientific evaluation indicates that there are reasonable grounds for concern that the potentially dangerous effects on the environment, human, animal or plant health may be inconsistent with the high level of protection chosen by the EU".

Clearly, for aviation, almost one decade after the first special report of the IPCC (1999), the above cited level of “preliminary scientific evaluation” has been reached. Different metrics for the non-CO_2 effects are in place and their merits and limits are known. It would thus conflict with the precautionary principle to preclude certain metrics from policy makers, since the latter may choose to use the precautionary principle and the best scientific information available, even knowing that it may be incomplete or uncertain.

Policy makers usually have an array of options at hand to handle uncertainty. These are among others the onus of proof, exemptions and review proceedings. Knowing e.g. that some of the non-CO_2 effects do not occur at flights below a certain threshold altitude, short distance flights could be exempted from applying a metric. For effects like contrail formation that depend on the ambient air mass, the onus of proof that no contrails formed on a certain flight could be laid upon the airlines. A review process could be installed to review the science and to incorporate progress of understanding in any measure applied. Whether or not these options are desirable and adequate or not comes down to a political decision.

Therefore, the conclusion of Forster et al. (2006) that it would be premature to include non-CO_2 effects into emissions trading seems to be difficult in two ways: On the scientific side it fails to put the uncertainty of the physical metrics into perspective with the uncertainty of other scientific matters such as discounting. Else it would acknowledge that even by having a quasi perfect physical metric, significant uncertainty for policy makers would still prevail. On the political side, it ignores that policy has the primacy over science when it comes to decision making. The IPCC states its work to be policy relevant but not policy prescriptive. According to the precautionary principle, it is not at the discretion of science to rule which metric is mature enough for policy making. Science may strive to reduce uncertainties, but the decision of what level of uncertainty is sufficient or not for political measures eventually is a political and not a science decision.

7. Conclusion

Based on the IPCC report 2007, this paper calculates and discusses the two existing metrics RFI and EWF. The RFI ranges from 1.9 to 4.7, which means a slight increase compared to the IPCC report of 1999. With a range of 1.2 - 2.7, the EWF (100 years) is smaller than the RFI. Thus, even when choosing a time horizon of 100 years the CO_2 emissions do not necessarily dominate the climate impact of aviation. The upper bound of the EWF lies in the middle of the RFI range. From a climate policy point of view, the RFI may be more meaningful than the EWF, since it better reflects the climate impact of aviation in those coming decades which are particularly important. On long time horizons both metrics reach the same numeric values. However, the EWF lags the RFI in showing the actual radiative forcing. From a policy point of view, both metrics provide insight for environmental policy making such as the inclusion of aviation into emissions trading.

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