A note on how to take into account the aircraft induced cloudiness in the EU-ETS

Andrew Ferrone , Philippe Marbaix
www.climate.be/abci, May 2009

The recent inclusion of the aviation sector in the European trading scheme is an important step forward that may help reaching a mitigation track consistent with the 2°C target of the European Union. However the proposed approach does not take into account the non-CO_2 effects of the aviation sector. Propositions regarding measures to limit the emissions of nitrogen oxides are in preparation and a study on this topic (Faber, 2008) was prepared on request by the European Commission. This note will thus focus on ways to include the contrails and cirrus clouds into the scheme and provide an incentive to mitigate these impacts while taking the tradeoff with the carbon dioxide emissions into account.

Measuring the aviation effects in a way that is appropriate for the emission trading and mitigation framework involves choices of definitions and objectives that imply value-judgments which should not be mistaken for scientific uncertainties. Trading requires that a common measure of impacts of different emissions types must be decided. For the Kyoto gases, it was decided that this is equivalent CO_2, an approximate measure of the global average climate effect over 100 years. Taking all uncertainties into account, our evaluation based on the existing literature (including effects of cirrus clouds excluded from many earlier analyses) is that a multiplier defined in this way should very likely be above 1.5[1], with a best guess value of 2.4 and the upper limit of the uncertainty range around 4. Moreover, the short term warming due to aviation induced cloudiness leads to additional emissions of CO_2 from the ocean and soil, provisionally estimated here to be equivalent to about 30% of the direct emissions of CO_2 from aviation, thereby converting this short-term forcing into an additional long-term effect.

As long as equivalent CO_2 as a common measure for all sources of climate change, the best way to take contrails and induced cirrus clouds into account would be to calculate equivalent CO_2 per kilometer flown in the actual conditions. For this to be possible further scientific studies are necessary and the very accurate accounting of the meteorological flight conditions are necessary. This is why we propose a multiplier that can be reduced if the airline takes measures to avoid the regions in the atmosphere where persistent contrails are prone to form. We propose to apply it in two steps:

To start, a multiplier equal to at least 1.5 would be applied to airlines that do not change the flight profile of their airplanes in order to avoid these regions (reverting to 1 for those that would systematically do the effort). In a next step, a multiplier could be calculated depending on the (unmodified) route flown, the time and the season. If mitigation is applied by following a route that keeps away from ice-supersaturated areas, this standard multiplier would be reduced by a factor that accounts for the induced cloudiness that is avoided

These measures could be applied quite easily and take into account some important tradeoffs. They also give a real insensitive to airlines to take the avoidance of the production of persistent contrails into account in their flight planning.

---

[1] It is sometimes believed that the IPCC (1999) reported a bottom range value of 2, but this was the lowest value given for the “radiative forcing index”, which is defined in a way that does not make it appropriate as a multiplier. In addition, our estimate is conservative as there are non-included effects – in particular the carbon cycle feedback that is mentioned below.

The following pages provide an overview of the requirements for the inclusion of non-CO_2 effects of aviation in the ETS and mitigation objectives through a " variable multiplier", the available scientific information to define its value, and remaining uncertainties.

1. What are desirable properties of a " variable multiplier" in the ETS context ?

The "multiplier" of emitted carbon dioxide is a way to count the climate impact of non-CO_2 emissions. These impacts are due to the "forcing" (net warming) of the climate system by nitrogen oxides (NOx, resulting in an initial short-lived warming by ozone and cooling by destruction of methane), the production of condensation trails (contrails) and their evolution into cirrus clouds, and smaller direct effects of sulfate aerosols, soot, and water vapor.

A requirement that appears critical is to maintain the consistency of the emission trading system:

1. Keep the trading as "neutral" as possible : a unit of gas traded by the aviation sector should have the same climate impact as a unit of gas originating in other ETS participating sectors

It is also desirable to define the multiplier so that there are no practical difficulties in its application:

2. Define the multiplier without ambiguity, in particular if it has a variable or revisable value

A specific difficulty of the aviation impact on climate is that it is not a constant proportion of the amount of consumed fuel or emitted CO_2. Other factors, such as the altitude of flight or engine type, may significantly change the consequences on the climate. This is particularly true at the regional scale, but it is possible that the fraction of climate change that is specifically regional could be better tackled by regulations outside the ETS. Indeed, the objectives of ETS relates to global changes, notably because the objectives are set in equivalent CO_2[2]. However, aviation has a global impact from non-CO_2 emissions, and for these emissions the specific characteristics of flights play a role in the climate impact. Therefore,

3. While using a fixed multiplier would have advantages compared to ignoring non-CO_2 forcings, full accounting for the aviation consequences on climate requires a measure of non-CO_2 impacts that depends on actual flight characteristics

Indeed, condensation trails can evolve into cirrus clouds only if the air in which they are formed is supersaturated. The parcels of supersaturated air are generally very thin, and a small change in flight altitude may reduce or avoid cirrus formation, depending on the meteorological conditions. These altitude changes can however increase the fuel use and thus the emissions of CO_2, therefore a tradeoff between these two effects needs to be made. A variable multiplier taking the actual flight impacts from both CO_2 and cirrus would provide an incentive to approach such optimal flight characteristics. It is evidently difficult to take into account the meteorological conditions for every

---

[2] If more weight is put on impacts that relates to certain regions (eg populated ones), changing the distribution of emissions will change the global effects on climate. It would not be possible to set a target in terms of global change in this case.

single flight, but a calculation based on the actual route, type of aircraft and eventual measures taken by the operator to avoid supersaturated regions could be used to reduce significantly the amount of data to collect and keep the scheme as simple as possible. It is also useful to note that these condensation tails are not taken into account, as in the current situation, the flights have on average more impacts on climate than the same amount of CO_2 would have if it was emitted in other EU-ETS sectors. Therefore, if companies buy allowances from non-aviation sectors, this would increase the actual impact on climate. The most simple way to solve this issue is to apply a fixed multiplier. This is not an optimal solution as no incentive to reduce contrail production would be provided, but the same problem exists in the current situation as any price of CO_2 (even without multiplier) is an incentive to ignore the trade-off with other effects.

2. Which “metrics” are available to define a multiplier?

Much of the debate around the value of the multiplier has focused on the "Radiative Forcing Index" (RFI), introduced by the IPCC (1999). It is defined as the ratio of total radiative forcing to that from CO_2 emissions alone. However, it was not supposed to be used as way to "aggregate" effects, as a "metric" to count all kind of emissions. In its last report (AR4, 2007, WG1, chap 2, page 215), the IPCC notes that the RFI "should not be used as an emission metric since it does not account for the different residence times of different forcing agents". A complete discussion of the properties of the RFI is longer, because this concept may take some account of residence times[3], but not in a consistent way. At the end, RFI is not a good candidate to be used as "a metric", that is, a measure of the effect of non-CO_2 gases, and thus it can't be used to build a multiplier.

The reference unit in this context of the emissions trading system is “equivalent carbon dioxide”. Based on IPCC-AR4, in the context of emissions, equivalent CO_2 is defined as the amount of carbon dioxide emission that would cause the same total radiative forcing, over a given time horizon, as an emitted amount of well mixed greenhouse gas(es). In simple words, it is an amount of CO_2 that would have roughly the same impact on climate as that of the considered gas. The equivalent CO_2 is obtained by multiplying the amount of emitted gas by its Global Warming Potential (GWP). The mathematical definition of GWP is given in annex I.

Equivalent CO_2 and GWPs are focusing on long term, global average effects: they are indicators of the effects on the climate over a given period, which is 100 years in the Kyoto Protocol[4]. The IPCC definition also reminds that it is made to measure global average effects, as it says that it is to be applied on “well mixed gases”, that is, gases that stay in the atmosphere long enough to reach an homogenous repartition over the planet. It is clear that equivalent CO_2 cannot take full account of all aviation effects, since most of the non-CO_2 effects are very short term – e.g. cirrus clouds produced by planes can only last days, with primary effects concentrated near the latitude of emission. As it is a long term global average, equivalent CO_2 cannot describe such regional differences. Stronger changes in some regions, or a tendency to cause faster climate change compared to CO_2 could cause more damage if it is caused by the short-lived processes due to planes than with the “equivalent” amount of real CO_2. The GWP based CO_2 equivalent is thus not a complete measure of impacts on climate. However, we are not looking for the perfect scientific

---

[3] Although it is not explicitly written in the above IPCC definition, practical uses of the RFI assume that the radiative forgings are computed for a given year taking into account *the accumulation* of emissions from a given sector *prior to the reference year*

[4] Decision 2 / CP.3, related to methodological issues

measure of the aviation impacts: the aim of our measure of aviation impacts is to integrate in an emission trading system. This is a different question, since the need is to have a common measure for impacts of different types.

GWP does not count short-term effects of aviation in a complete manner, but it does count all gases in a consistent way (average effect, over 100 years). It is not "wrong" from a scientific viewpoint, it is merely incomplete. However, it seems logical that any aggregated measure of the very different effects of short-lived and long-lived emissions would be unable to measure their possible consequences in a complete manner, in particular because the difference between short and long term effects will depend on the future path of global emissions for all sectors. The details of the "value" of contrails vs carbon dioxide warming potentials is not defined a priori without knowing these future emissions. A frequent misunderstanding is that the key issue is a lack of scientific data or understanding: in fact there are fundamental limitations to the use of an aggregated measure of climate warming (or damages) potential. Research may help in making sound choices, but there is already enough understanding of aviation impacts to conclude without ambiguity that aviation is having more global scale effects on climate than those from CO_2 alone.

The use of equivalent CO_2, while not fully measuring aviation effects, can provide a measure of these long term ones. Their inclusion in a cap-and-trade system in which each factor is counted using is GWP may possibly be supplemented by regulations concerning short-term effects. This would be particularly justified in Europe, as short-term effects are also local effects that are larger around the latitude of emission.

Other aggregate measures of non-CO_2 effects have been proposed. An example is the global temperature potential (GTP), which is defined as the ratio between the global mean surface temperature change at a given future time horizon following an emission of the considered compound relative to the reference gas (e.g., CO_2) (IPCC AR4, 2.10.4). The considered emission can be a "pulse" at the beginning of the period or an emission sustained throughout the period. While the GWP is an integral quantity over the time horizon (i.e., the contribution of the RF at the beginning and end of the time horizon is exactly equal), the GTP uses the temperature change at the end of the selected period: radiative forcing closer to the end contributes relatively more. As noted by Forster et al. (2006), there is a near equivalence between the GTP for sustained emission changes and the GWP (defined for a pulse emission). The GTP metric has the potential advantage over GWP that it is more directly related to surface temperature change (it may include "efficacies" that relates radiative forcing to temperature changes). In the context of trading, the requirement is to count the effects of present emissions, so that the focus is on the "pulse" variant of the GTP metric. As only temperature changes at the end of the period are counted, effects at the beginning of the period will only be seen through feedbacks and inertia in the climate system, so that gases that have short lifetimes will be weighted less with GTP than with GWP. It is possible that the GWP offers a more balanced measure of the impacts of short and long lived emissions.

As there are different types of agents that have an impact on climate, involving very different time scales (from days to centuries), no single metric can measure all aspects of impacts; in addition, impacts of a given gas are dependent upon the future emissions of other gases. Thus any single metric is a compromise. In conclusion, while there is scope for more research regarding measures of impacts of climate altering atmospheric emissions, the GWP metric currently used in international agreements, as well as the energy metric, which is gives an easy to understand metric, are both valuable. Its replacement would require careful assessment of potential new measures or improvements.

3. What do we know about multiplier values and uncertainties ?

Following the discussion in section 2, we focus on GWP as a measure of non-CO_2 impacts compared to those from CO_2. It is a consistent metric that reasonably satisfy the first two criteria set out in section 1 (criteria 3 is discussed in the last section), and in addition it is the one used in the ETS. The detailed definition of the GWP-based multiplier[5] is given in Annex I. As explained above, it approximately represents the total average climate impact over a given period compared to that of CO_2 alone. While climate policy focuses on the 100 years time average, we also computed the multiplier for a 20 years average to illustrate the fact that focusing on shorter term impacts results in larger impacts of non-CO_2 (mostly short term) agents compared to CO_2, which means higher multiplier values. It is important to note that all these results are derived from existing studies (see appendix) that we combine to provide a GWP-based multiplier including all significant impacts: NO_x (ozone and methane effects), contrails, induced cirrus (excluded from many earlier analyses) :

	Components of non CO_2 impacts (as fraction of the total non CO_2 impacts)			multiplier (all impacts)		
	NOx	contrails	cirrus	low	best estimate	high
20 years	2 – 4%	14 – 37 %	60 – 83%	2,7	6	12
100 years	-0,2 – -0,5 %	14 – 38%	63 – 86%	**1,5**	**2,4**	**4,1**

The scientific uncertainty related to each effect as it has been evaluated in the existing literature was taken into account to provide a range for the multiplier values, which are in accordance with Fuglestvedt et al. (2009) Seeing that ,following the current scientific understanding contrails and their evolution into cirrus clouds plays a more important role for climate than the NO_x emissions the rest of this paper will focus on the aircraft induced cloudiness.

Additional effect of carbon feedback

The above figures takes into account all the major effects that have been discussed in the literature. However, they are still conservative estimates at least one important effect that was not taken into account: the short term warming due to non-CO_2 effects leads to an additional positive feedback (= an amplification of the change) in the carbon cycle that converts this short-term forcing into a long-term effect.

The soil respiration and the atmosphere-ocean chemistry are both dependent on the temperature. An augmentation of this temperature will lead to an increased concentration of CO_2 in the atmosphere, thus leading to more warming and giving a positive feedback on the increase of temperature.

An investigation of this effect with the *Java Climate Model" (appendix II), using a scenario consistent with the calculations of the AGWP showed that this feedback effect adds an additional 21% to the cirrus+contrail forcing. Comparing to the uncertainty of the forcing this number seems relatively small but it also converts this short-term pulse forcing into a long-term effect (this "indirect" aviation CO_2 is an extra 30% on top of "direct" aviation CO_2 emissions). Therefore, even when considering only long term effects, this (non-CO_2) effect should be taken into consideration.

---

[5] Also called emissions weighting factor (EWF)

This additional forcing is also much less sensitive to the time-horizon considered than the total aviation forcing, since it only involves CO_2 (rather than a mix of other agents with short and long term impacts that needs to be converted to a common unit), so its relative importance is less dependent on a methodological choice involving a value judgment.

4. What are potential contrail mitigation options?

The implementation of technological options to inhibit the production of contrails are not effective, or not practical (see Gierens et al., 2008), thus air traffic management regulations have to be envisioned in order to reduce the impacts of cirrus clouds formed by air traffic.

In-situ measurements and models show that most ice-supersaturated regions (ISSR) occur between an altitude of 7 to 10 km, the region in which planes are currently flying. A permanent avoidance of flight levels where most of contrails would only avoid approximately 50 % of persistent contrails, if a reduction of 6000 ft (approx. 2000 m) would be imposed (see figure 1,red line and Mannstein et al., 2005). Due to higher air density at this reduction in flight altitude would drastically increase fuel burn and thus the emission of carbon dioxide. Moreover this would reduce the number of available flight levels and increase the congestion of the airspace especially in regions with high air traffic density like Europe.

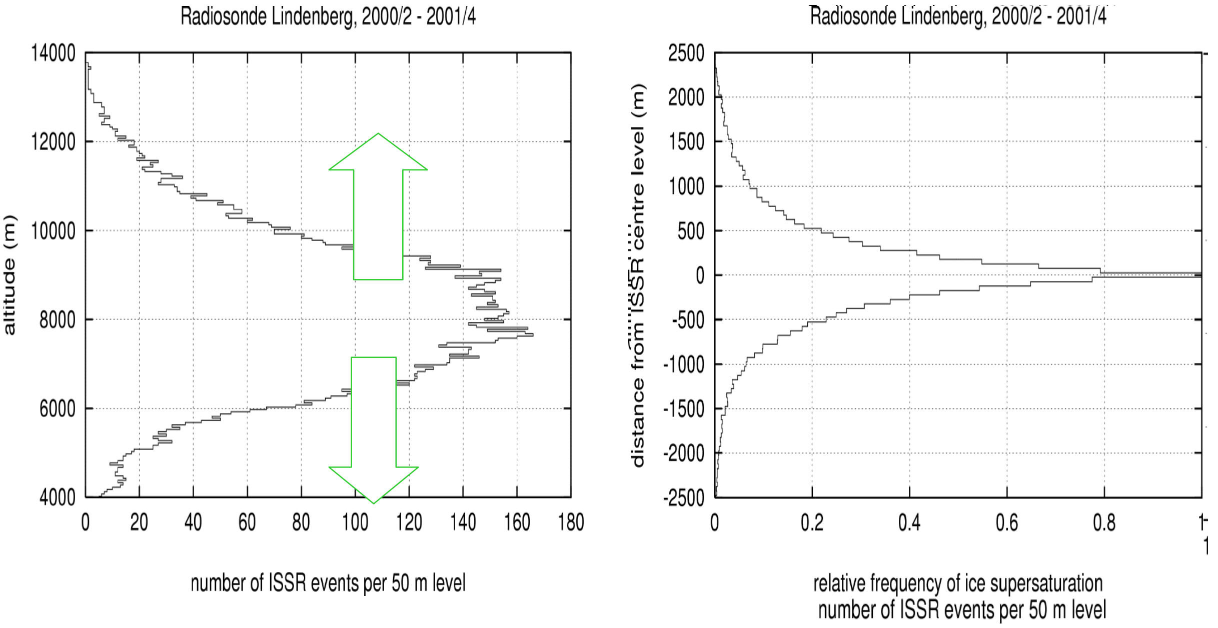

Figure 1: The left panel shows the number of occurences of ISSR in the radio sonde data, lauchned from Lindenberg (Germany) between February 2000 and April 2001 as a function of altitude. The right panel shows the distribution frequency of the thickness of the layers in the same dataset as the right panel

However as can be noticed from everyday observations, but also from radiosonde and satellite measurements, ISSR occur less than 10 % of the time at a given location (see figure 1) and the layers of ice supersaturation are in general very thin (a mean of 300 m, but can be up to a few km thick). Both of these characteristics can be used to avoid ISSRs. Figure 1 also shows (dark green line) that a change (up or down) of altitude of only 1000 ft can avoid 50% of contrails production, and a change of 2000 ft (approx. 600 m) if the plane would fly through a ISSR can avoid more than 80% of persistent contrails.

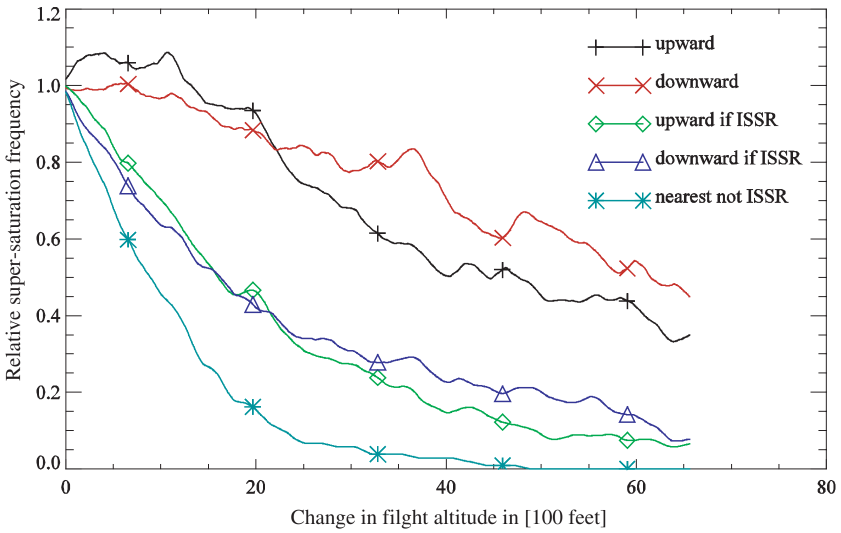

Figure 2: The relative probability to fly still in super-saturated air after a flight-level change from FL 290 (approx. 8700 m). Red/black line the change is made upward/downward independently of the flight conditions. Green/blue the change is made upward/downward if FL290 is in a ISSR. Cyan, the change is made if FL290 is in an ISSR and to the nearest layer that is not ice-superasturated.

Mannstein et al., 2005 suggest to detect the ISSR directly on the airplane (with an installed hygrometer or a camera) and to perform a change in altitude (in acceptance with air-traffic control) if the airplane is producing a persistent contrail. Such a measure is technically relatively simply to implement, however as every change of altitude would produce an increase of fuel use this would lead to an unnecessary increase of fuel use as plane would need to carry additional fuel (and thus weight) even on flights were no changes would have to be made.

The German UFO project (http://www.pa.op.dlr.de/ufo/) is currently analyzing how to include the forecasts of ISSR by the weather service in the planning of the flight. The latest numerical weather prediction models do allow the forecast of these regions and this information could be used to optimize the flight plan accordingly to the avoidance of contrails and the additional fuel used.

In order to work such tools need to put a price on the contrail impact in order to be able to cope with the trade-off of fuel use and contrail avoidance. In order to test the tool a case-by-case multiplier, based on a reformulation of the GWP-metric is used and multiplied with actual price of carbon in the ETS.

Such a multiplier based on a case-by-case study could be used in the ETS depending on the length, location and lifetime of the contrail formed. However the amount of data that would be needed (flight location, type of aircraft, thrust settings, location of ISSRs, calculations of properties and life-time of the contrails) and the uncertainties associated with the results make such an inclusion impractical for the moment.

This is why we propose to use a multiplier that can be calculated on the basis of the route, the daytime and season of the flight based on climatological information of ISSR (e.g. Gettleman et al., 2005). The distinction of different routes is needed as contrails formed over dark surfaces and at daytime have a less impact (due to strong albedo effect) than contrails formed at night, or over highly reflective surface (e.g. snow or ice).

Once the multiplier has been fixed for a route it would only be applied to those airlines that do not take any measures to avoid the ISSRs. Those airlines that take these regions in account and change flight levels to avoid them if the additional CO_2 produced has not a stronger impact on climate, would be partly exempted from the multiplier.

5. Conclusion and discussion

The recent inclusion of the CO_2 emissions by the aviation sector in the EU-ETS is a much welcome progress. However, other impacts of aviation on climate will also need to be tackled. These include in particular a contribution to the formation of cirrus clouds, which is very likely to represent a major fraction of aviation impacts, and the effects of nitrogen oxides (NOx, contributing to short term warming by ozone but with little long term average impact, following destruction of methane). Counting all these impacts may seem difficult, but it is important to note that it is not primarily due to scientific uncertainties : a key issue is that trading requires that a common measure is constructed for the different types of emissions. However, no single metric can provide a complete view on all aspects of impacts of which some are very important in the short term and others in the long term, and with climate impacts from one gas influenced by future emissions of others : value judgments and compromises are needed.

Taking all uncertainties into account, our evaluation based on the existing literature (combined to include the effects of cirrus clouds) is that a multiplier defined in this way should very likely be above 1.5, with a best guess value of 2.4 and the upper limit of the uncertainty range around 4. Moreover, the short term warming due to aviation induced cloudiness leads to additional emissions of CO_2 from the ocean and soil, provisionally estimated here to be equivalent to about 30% of the direct emissions of CO_2 from aviation.

As noted at the end of section 1, a fixed multiplier based on these figures appears better than ignoring aircraft induced cloudiness, but does not provide an incentive to reduce these non-CO_2 impacts of aviation. We thus suggest four possible ways to include aircraft induced cloudiness, ordered by increasing accuracy and complexity, so that these could be applied successively :

- 1- To start, use a fixed multiplier with a value depending on the policy choice regarding uncertainty – i.e. either the best guess estimate (2.4) or another value in the uncertainty range (1.5 - 4) [6], with the possibility to update if science is progressing.

- 2- In addition to (1), cancel the multiplier (i.e. revert to 1) for the flights for which meteorological conditions were verified, and the flight profile adapted if needed,,to avoid the formation of persistent contrails;

- 3- To refine the standard multiplier, compute values depending on the (unmodified) route flown, the time and the season. If mitigation is applied by following a route that keeps away from ice-supersaturated areas, this standard multiplier would be multiplied by a factor that accounts for the induced cloudiness that is avoided (the non-CO_2 contribution would be multiplied by the remaining cloudiness, e.g. if for the given route the multiplier would be 3, and 80 % of the contrails are avoided compared to the baseline, the applied multiplier would be 1.4)

---

[6] Using the higher end may represent an application of the "precaution principle", although the feedbacks on carbon would still be excluded. However, logical progression with the next steps of inclusion of these effects may rather suggest the use of a value near the low end of the uncertainty range (ie comming from 1 = non-CO_2 effects excluded, to 1.5 = first step, partial inclusion, then higher values in the next steps.

- 4. The final step would be to explicitly include the contrails in the EU-ETS by directly weighting their impact in a common unit (e.g. equivalent CO_2 as in the Kyoto Protocol) without assuming proportionality to fuel use. Expressing the effects of contrails and cirrus clouds in such a unit is not easy, as the creation of condensation trails cannot be expressed in terms of mass (it is not possible to count "tons of contrails"). This problem cloud be solved by expressing their climate impact per km flown, because the formation of these clouds does mainly depend on the distance flown (not on the burned fuel). It could thus be possible to calculate an equivalent CO_2 amount per km. However, different types of planes and engines may be more or less prone to induce cloudiness (see Sussmann et al., 2001), so that further research is needed before such a measure could be used.

We think that this approach in four steps may help taking all the impacts of aviation into account rapidly, to quickly provide incentives to operational measures (adaptation of the flight profiles to avoid ISSR) and also to encourage further scientific studies (improving the quantitative knowledge of the effect of contrails on climate and further evaluate the response measures).

From the second step, Tradeoffs between the short-term lived contrails and cirrus clouds and long-term carbon-dioxide effects would be taken into account, however we think that a quite simple measure is needed as a first step, before progressively including these effects completely (and independently of fuel use) into an emission trading scheme.

The authors thank the Belgian federal science policy for its support under contract SD/CP/01A "Aviation and the Belgian Climate Policy: Integration Options and Impacts" (ABC Impacts). A. Ferrone is supported by the Belgian National Fund for Industrial and Agricultural Research (FRIA).

Appendix 1 : definition and computation of the GWP-based multiplier

The GWP of a component i, is the time integrated radiative forcing following a pulse emission of 1kg of i, also called absolute GWP (AGWP), divided by the corresponding value for the reference gas (here CO_2). For a time horizon of 100 years (IPCC AR4):

$$GWP_i = \frac{AGWP_i}{AGWP_{CO_2}} = \frac{\int_0^{100} RF_i(t)\, dt}{\int_0^{100} RF_{CO_2}(t)\, dt}$$

The role of the emissions weighting factor (EWF, or multiplier) is to obtain the amount of CO_2 equivalent ($Q_{CO_2 eq}$) corresponding to all emissions from air traffic that generated a given quantity of actual CO_2 (Q_{CO_2}). This total equivalent CO_2 is given by the sum over all types of radiative forcing caused by aviation of its GWP times its amount:

$$Q_{CO_2 eq} = EWF\ Q_{CO_2} = \sum_i Q_i GWP_i$$

The multiplier (also called emission weighting factor), is thus the weighted sum of the GWPs (CO_2, O_3, CH_4. linear contrails and induced cirrus clouds):

$$EWF = \sum_i \frac{Q_i}{Q_{CO_2}} GWP_i = \sum_i \frac{Q_i}{Q_{CO_2}} \frac{AGWP_i}{AGWP_{CO_2}}$$

As we are dealing with long term (100 years) effects, we may compute the multiplier on the basis of emissions over one year rather than instantaneous emissions. This allows us to compare the average impact of contrails, which cannot be measured in units of mass to the emissions of other gases emitted by aircraft.

The AGWP for CO_2 is taken from AR4, the radiative forcing for contrails and cirrus clouds for the year 2000 is taken from (Sausen et al., 2005 and Lee et al.,2009) and the fuel use for the same year is taken from "Java Climate Model" (based in particular on UNFCCC greenhouse gas inventory data). Finally the AGWP for NO_x emissions of aviation in 2000 is taken from (Forster, 2006).

Combining these sources, which give the most up-to-date information, we can derive the EWF given in table in section 3 (page 5), as well as the importance of the non-CO_2 effects as a fraction of the EWF.

Appendix 2 : Additional impacts due to Climate-Carbon feedbacks

Regarding the additional forcing from CO_2 caused by aviation contrails and cirrus, via climate-carbon feedbacks, some preliminary calculations were made in UCL/ASTR using the "Java Climate Model" (see www.climate.be/jcm/jcm5).

Results are given for the default setup of the model (version July08), whose carbon cycle includes the feedback of global warming on soil respiration and on surface-ocean chemistry, with parameters tuned to fit the average from AR4 WG1 Table 7.4. In this case the 100-year AGWP for CO_2 gave a value 3% lower than that from AR4 WG1 Section 2.10.2, whose uncertainty range is given as ±15%. The baseline scenario used was set as close as possible to that used for GWPs as in AR4, i.e. constant concentration fixed at 380ppm, (except for an initial peak at 393 consistent with recent emissions).

The corresponding 100-year AGWP for additional CO_2 (integral over the following 100 years) due to the same pulse of cirrus and contrails adds 21% to the cirrus and contrail forcing (integral over one year). This could apply to any short-lived gas (not only those from aviation). Or saying it differently the additional forcing from "indirect" CO_2 due to aviation cirrus+contrails, via climate-carbon feedbacks, is 30% of that from the direct aviation CO_2 emissions. These numbers are also much less sensitive than the GWP to the time-horizon considered, and so are less dependent on a methodological choice involving a value judgement.

Some caveats should be noted :

- This effect is scenario dependent, as is the AGWP for CO_2. Both figures will be lower for higher scenarios, as each additional ppm of CO_2 has less effect on the radiative forcing due to saturation of the absorption band (which outweighs the other effect of increased CO_2 lifetime due to higher temperature and sink saturation in higher scenarios). For comparison the 100-year AGWP for CO_2 calculated with JCM for the A1B scenario is 18% lower, and the equivalent figure for the aviation cirrus and contrails is 15% lower.
- This extra effect should only be included in a GWP calculation if similar climate-carbon feedbacks are also taken account in the AGWP for CO_2. We presume that this was the case for the AR4 AWGP for CO_2 calculated using the Bern2.5CC(2001) model which incorporates the LPJ dynamic vegetation model.
- These calculations are calculated using a simple global upwelling-diffusion energy-balance model, in which the climate-carbon feedbacks (both land and ocean) are based only on the global average temperature. In reality these feedback effects apply regionally, and so it might be expected that the effect of the aviation forcing would be even greater because aviation is concentrated over land at northern mid-latitudes, the same zonal band as the majority of global soil carbon stock, and also because the direct effect of aviation cirrus on sunlight and hence photosynthesis might also reduce the carbon uptake of plants. On the other hand, this calculation does not include any "efficacy" factor (which would reduce the effective global forcing of aviation cirrus).
- The magnitude of climate-carbon feedbacks is highly uncertain, as indicated by the range of C4MIP results in AR4 WG1 Table 7.4. Later work will explore the effect of using the full range of results from C4MIP to tune the carbon cycle parameters - (this is anticipated to affect the result for C-C feedback AGWP by >100%).
- Climate-carbon feedbacks in JCM are calculated using the global average temperature from the previous year, consequently the effect of the short-term time-profile of the temperature peak due to the pulse of forcing is not properly taken into account. Later work may explore the effect of reducing the timestep of this part of the model.

References

ABC Impacts, 2008. *Aviation and the Belgian Climate Policy: Integration Options and Impacts, Final report for phase I*, http://www.climate.be/abci

Faber J., D Greenwood, D Lee, M Mann, P Mendes de Leon, D Nelissen, B Owen, M Ralph, J Tilston, A van Velzen, G van de Vreede. *Lower NOx at Higher Altitudes Policies to Reduce the Climate Impact of Aviation NOx Emission*. Delft, CE Delft, October 2008

Forster, P. M., K. P. Shine, N. Stuber, 2006. *It is premature to include non-CO_2 effects of aviation in emission trading schemes*. Atmospheric Environment, Vol. 40, 1117–1121

Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M., Waitz, I.A. *Transport Impacts on Atmosphere and Climate: Metrics*, Atmospheric Environment (2009), doi: 10.1016/j.atmosenv.2009.04.044

Gettelman, A.W., D. Collins, E.J. Fetzer, A.Eldering, F. Irion, W. P. B.Duffy, and G.Bala, 2006, *Climatology of upper tropospheric relative humidity from the atmospheric infrared sounder and implications for climate*. J.Climate, 19(23):6104–6121.

Gierens K., Lim L. and Eleftheratos K., 2008. *A Review of Various Strategies for Contrail Avoidance*. The Open Atmospheric Science Journal, Vol. 2, 1-7

IPCC, 1999: Aviation and the Global Atmosphere: A Special Report of IPCC Working Groups I and III [Penner, J.E., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 373 pp.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lee, D.S., D.W. Fahey, P.M. Forster, P.J. Newton, R.C.N. Wit, L.L. Lim, B. Owen, and R. Sausen, *Aviation and global climate change in the 21st century*, Atmospheric Environment (2009), doi: 10.1016/j.atmosenv.2009.04.024

Mannstein H. , P.Spichtinger, and K.Gierens, 2005 *A note on how to avoid contrails*. Transportation Research, D(10):421—426.

Marais K., S. P. Lukachko, M. Jun, A. Mahashabde and I. A. Waitz. *Assessing the impact of aviation on climate*, 2008. Meteorologische Zeitschrift, Vol. 17, No. 2, 157-172.

Sausen R. and I Isaksen and V. Grewe and D. Hauglustaine and D. S. Lee and G. Myhre and M. O. Köhler and G. Pitari and U. Schumann and F. Stordal and and C. Zerefos, 2005. *Aviation radiative forcing in 2000: An update on IPCC (1999)*. Meteorologische Zeitschrift, Vol. 14, 555-561

Sussmann R., and K. M. Gierens ,2001. *Differences in early contrail evolution of two-engine versus four-engine aircraft: Lidar measurements and numerical simulations*, J. Geophys. Res., 106(D5), 4899–4911.