CLIMATE IMPACT OF A POTENTIAL SUPERSONIC FLEET

V. Grewe
Institut für Physik der Atmosphäre, DLR-Oberpfaffenhofen
82234 Weßling
Germany

OVERVIEW

Within the EU-project SCENIC the impact of a potential supersonic fleet has been investigated. The methodology how to estimate its climate impact is presented. A number of sensitivity studies are analysed to identify options to minimise climate impact. Since stratospheric water vapour emissions are the most important contributor to climate change induced by supersonics those scenarios are minimising the climate impact which have the lowest cruise altitude.

In order to include climate aspects in multi-disciplinary optimisation for supersonics an assessment tool (AirClim) has been developed within the EU Integrated Project HISAC, which is briefly presented. The main atmospheric input data describe the atmosphere's sensitivity to the emission region. Based hereon a functional relationship has been developed between basic (supersonic) aircraft design parameters (cruise altitude, fuel consumption) and climate change.

1. INTRODUCTION

Air traffic has the potential to grow over-proportional compared to other transport sectors. Its specific climate impact, i.e. relative to fuel consumption is larger than for other sectors (Fuglestvedt et al., 2007). One reason is the higher altitude of the emission, which leads to longer atmospheric residence times, e.g., in the case of NO_x emissions and its chemical products (ozone). Therefore, there is a need to develop technical and operational options to reduce the impact from air traffic emissions on climate and to provide tools to reliably assess these impacts, or at least to provide some skill scores for various options within an uncertainty range. In this context it is important to note that a simple metric based on fuel consumption or emission indices insufficiently describes the total climate impact. The dependency of the strength of the impact on altitude and region cannot be described by such metrics. E.g., contrail formation depends on aircraft design aspects (propulsion efficiency), water vapour emission (directly related to fuel consumption), but also and equally important on local atmospheric conditions (Schumann et al., 2000).

In the following a brief overview on the atmospheric impact of a potential supersonic fleet is given. The results are obtained within an EU project (SCENIC). Results are published in a Special Issue in "Atmospheric Chemistry and Physics" (Grewe et al., 2007; Søvde et al., 2007; Stenke et al. 2007). Here, basically results from Grewe et al. (2007) are summarised. Within the EU Integrated Project HISAC the methodology has been considerably refined and a linear response model developed (AirClim; Grewe and Stenke, 2007; Section 3), which efficiently converts emissions into a metric for climate change, e.g., near surface temperature change. For supersonic applications these results were used to obtain a simple formula to describe the main climate aspects in terms of aircraft parameters.

2. CLIMATE IMPACT OF A SUPERSONIC FLEET

2.1. Emission scenarios

Within the EU-project SCENIC a supersonic base case scenario has been developed by AIRBUS (C. Marizy, pers. comm.). A 250 passenger aircraft was considered with a range of 5400 nm, which comes into service in 2015, a first fleet fully operational in 2025 (Scenario S2) and a second in 2050 (S5). All scenarios were design to have the same transport volume, i.e., in S5 supersonic aircraft replace subsonic aircraft.

For sensitivity studies and to find a climate impact minimising fleet, which still is economically viable, a number of sensitivity studies were performed. A variation in the NO_x emission index (P2), fleet size (P3), Mach number (P4), range (P5) and cruise altitude (P6) has been considered (Tab. 1).

	Aircraft number	Speed	Maximum range	Cruise height	Fuel burned		$EI(NO_X)$	
		MN	nm	kfts	Tg/y		$g(NO_2)$ /kg(fuel)	
	Supersonic parameters				Tot.	Sup.	Tot.	Sup.
S4–Sub	0	-	-	-	677	0	10.85	-
S4-core	0	-	-	-	659	0	10.85	-
S5–HSCT	501	2.0	5400	54-64	721	60	10.33	4.60
P2–EI	501	2.0	5400	54-64	721	60	10.74	9.63
P3–Size	972	2.0	5400	54-64	762	115	9.90	4.62
P4–Speed	544	1.6	6000	47-59	703	41	10.53	5.42
P5–Range	558	2.0	5900	53-65	733	74	10.41	6.61
P6–Height	561	1.6	5900	43-55	702	40	10.55	5.62

TAB 1. Overview on the SCENIC emission dataset.

2.2. Methodology

Within the SCENIC project 4 climate-chemistry models were applied to calculated changes in atmospheric concentration of chemical species and changes in contrail cover. All changes consider the substitution of subsonic aircraft by supersonic aircraft, i.e. difference between two simulations are regarded, one including S5 emissions and one including S4 emissions. Those change patterns were used to calculate the respective change in radiation at the boundary between troposphere and stratosphere. This so-called radiative forcing (RF) is proportional to steady-state global mean changes in near surface temperature and therefore a good metric for climate change, at least for well-mixed greenhouse gases. Temporal changes in temperature (*ΔT*) can be estimated based on these RF values and some overall assumptions for air traffic development between 1990 and 2100. This takes into account inertia of the ocean-atmosphere system and applying Green's functions (G_T) to this system, which is fully described in Sausen and Schumann (2000) and Grewe et al. (2007):

$$\Delta T(t) = \int_{t_0}^{t} G_T(t-t') \times RF^*(t')\, dt' . \qquad (1)$$

RF^* is a normalised RF, which takes into account individual climate sensitivities of the regarded specie.

2.3. Carbon Dioxide - CO_2

Carbon dioxide has a long atmospheric residence time (~100 years). This means that although emissions are kept constant after 2050 for this example (Fig. 1), the concentration and RF will still increase. When we consider additionally the inertia of the ocean-atmosphere system in the temperature response (Eq. (1)) it becomes evident that the climate impact of sustained CO_2 emissions has time-scales in the order of a century.

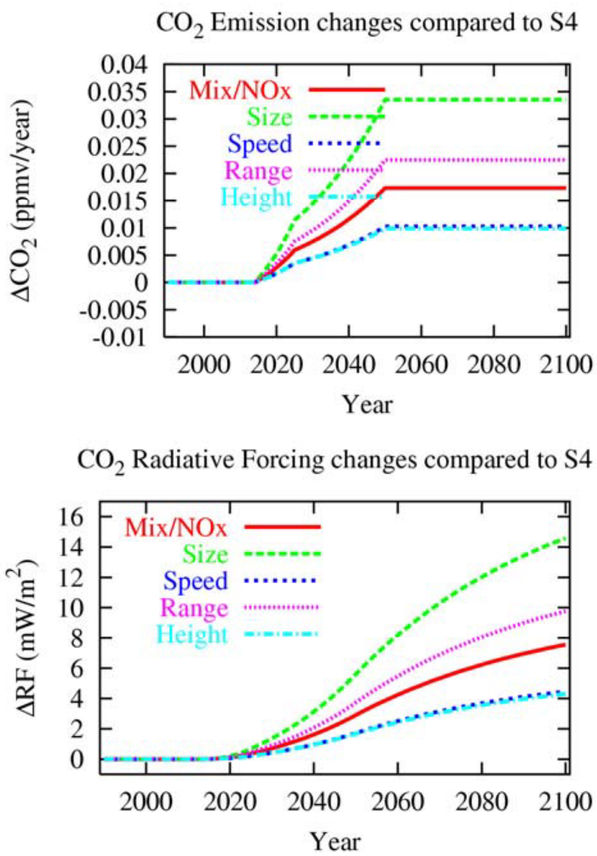


FIG 1. Top: Emissions scenarios for CO_2 with respect to a base case supersonic scenario (S5). Bottom: RF from these emission scenarios.

2.4. Water vapour – H_2O

The emission of water vapour is directly linked to the fuel consumption with 1.25 kg water vapour emitted per 1 kg fuel burnt. In contrast to carbon dioxide, the atmospheric impact depends on the emission region. The higher the emission occurs, the longer is the residence time of the water vapour perturbation. Subsonic air traffic emit in the tropopause region or directly in the troposphere, where water vapour has such a short lifetime that its emission cause only minor changes to the water vapour concentration. However, supersonic transport emit directly in the stratosphere, where the residence time may be as large as 2 years for such a perturbation. Hence accumulation plays a role, which makes water vapour to the most important emission with respect to climate change. The four atmosphere-chemistry models calculated maximum changes of water vapour in the range of 250 to 350 ppbv, which is in the order of 5-10% of the background concentration.

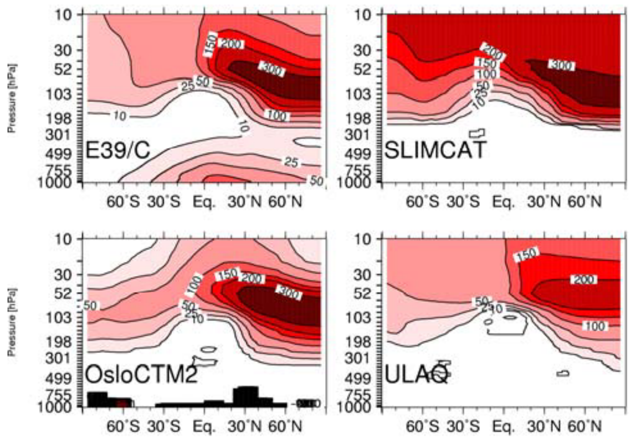


FIG 2. Multi-annual mean water vapour concentration [ppbv] as a difference of 2 simulations one with a mixed fleet (S5) and a subsonic-only fleet (S4). Calculations are performed with 4 atmosphere chemistry models.

2.5. Nitrogen oxides - NO_x (=$NO+NO_2$)

Nitrogen oxide emissions have a different impact depending on the emission region. In the troposphere, e.g. at 5 km altitude, emissions of NO_x lead to production of ozone, whereas in the stratosphere, e.g. at 20-30 km altitude, NO_x tends to deplete ozone, i.e. reduces the ozone layer. The turn around point is not yet well

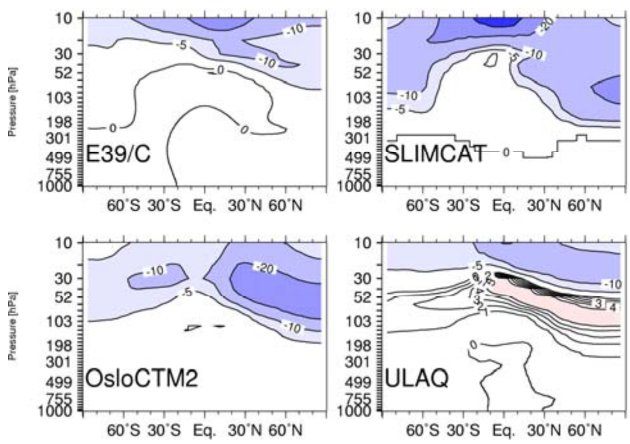


FIG 3. Multi-annual mean ozone concentration [ppbv] as a difference of 2 simulations one with a mixed fleet (S5) and a subsonic-only fleet (S4). Calculations are performed with 4 atmosphere chemistry models.

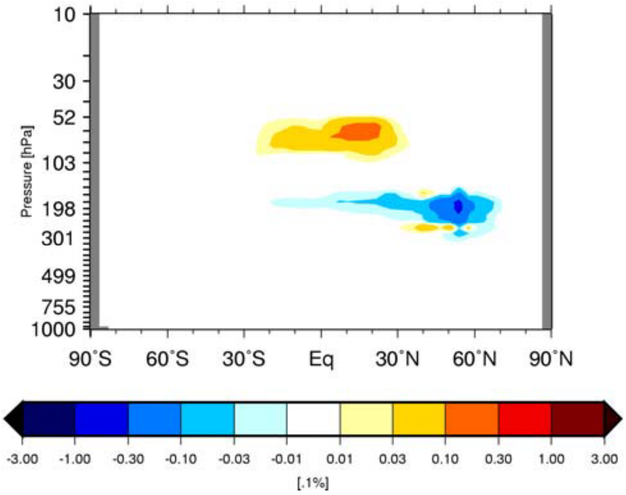


FIG 4. Multi-annual mean contrail cover change caused by a substitution of subsonic by supersonics (S5-S4).

determined, but is currently estimated to be in the range of 14 to 17 km. NO_x emissions increase the amount of nitrogen compounds (NO_y). Its change pattern derived from a simulation with a mixed fleet (S5) with respect to a subsonic fleet (S4) shows a similar pattern as for water vapour, since stratospheric loss terms are comarable (FIG 2). The impact on ozone is simulated very differently among the models (FIG 3). However, all models show ozone depletion at high altitudes. Some models additionally show an ozone increase at lower altitudes.

Changes in ozone lead to changes in the concentration of the hydroxyl radical OH, since the photolysis of ozone leads to oxygen atoms which partly recombine with water vapour to form OH. OH is one of the most reactive

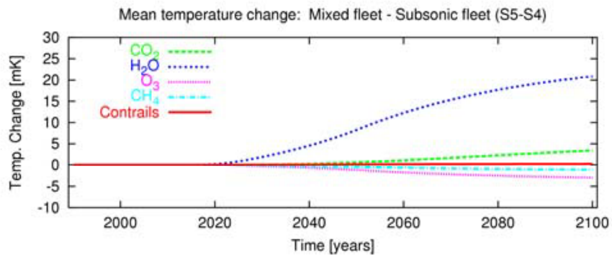


FIG 5. Temporal development of the temperature changes due a substitution of subsonics by supersonics (S5-S4).

atmospheric species and reduces the abundance of the greenhouse gas methane. The lifetime reduction of methane was estimated in the range of 0.1% to 0.4%.

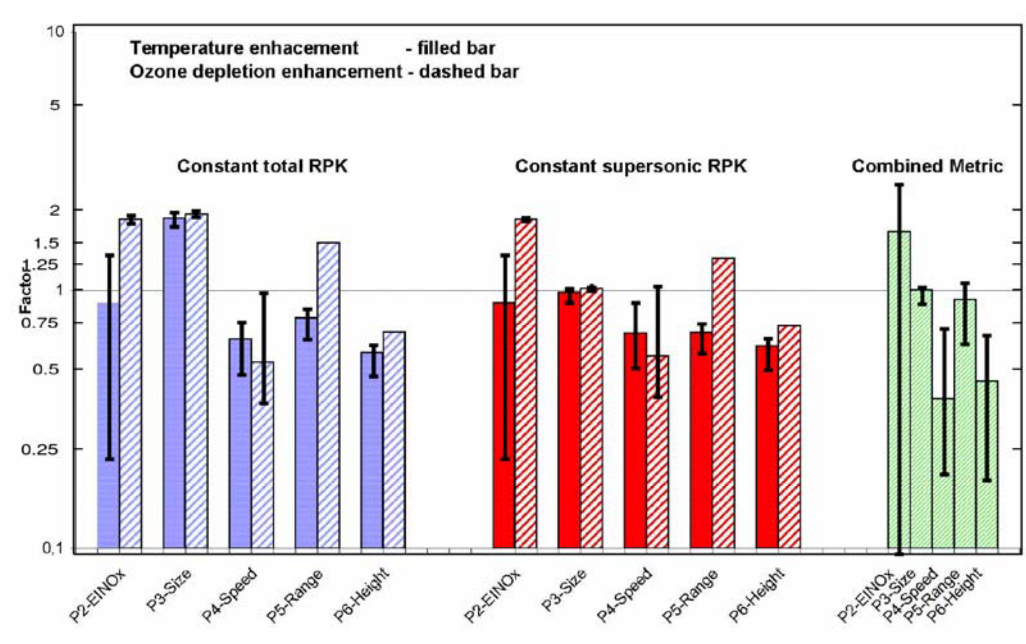
2.6. Contrails

Generally, supersonic aircraft were considered not to form contrails, because they fly in stratospheric regions, which are too dry to allow for contrail formation (IPCC, 1999). However, this is only valid for mid-latitudes. Stenke et al. (2007) (FIG 4) showed that a replacement of subsonics by supersonics leads to only minor decreases in the contrail formation, since the decrease in contrail cover at mid-latitudes is compensated by contrail cover increase at low latitudes.

2.7. Supersonic fleet with minimal environmental impact

Sections 2.3 to 2.6 described the impact of a replacement

FIG 6. Changes in near surface temperature for the year 2100 (solid bars) and for ozone (dashed bars) for constant transport volume of the total fleet (blue) and constant supersonic transport volume (red). The product of both factors is added (green) as an overall metric. For each bar an uncertainty range is given, which represents minimum and maximum values.



of subsonic aircraft by supersonics on the atmosphere in terms of concentration changes. From those changes the RFs and the associated temperature change calculated by applying the above describe methodology (Section 2.2). Figure 5 shows the temporal development of temperature changes caused by a replacement of subsonics by supersonics (S5-S4). Clearly water vapour is the most important contributor to the overall climate change induced by this substitution.

As described above supersonics have two major impacts on the atmosphere. They change total ozone column (ozone mass) and hence UV-radiation and they have an impact on climate change mainly via water vapour emissions. Both metrics, ozone mass and near surface temperature increase, were estimated for all of the scenarios described in TAB 1. Figure 6 shows relative changes of all perturbation scenarios (P2-P6) with respect to the base case (S5-S4), i.e., $\frac{P2-S4}{S5-S4},...,\frac{P6-S4}{S5-S4}$. In green a combined metric is shown, which simply is the product of the two metrics. Clearly, the two scenarios, which minimize the cruise altitude and speed, have the lowest impact.

Although a number of studies have investigated the impact of subsonic air traffic (e.g., IPCC, 1999; Sausen et al., 2005) and supersonic air traffic (e.g., IPCC, 1999; Grewe et al., 2007) a direct intercomparison of subsonic and supersonic aircraft cannot be performed on that basis. RF and ΔT are metrics, which include a history of emissions. Sausen et al. (2005) concentrated on subsonics from 1950 to 2000, whereas Grewe et al. (2007) investigated the climate impact of supersonics from 2015 to 2100. Hence the time horizon as well as the transport volume differs significantly which makes an intercomparison meaningless. This gap has been identified by the EU-Network of Excellence ECATS and a study was conducted to estimate the impact of comparable aircraft – subsonic and supersonic, with the same transport volume and time horizon (Grewe and Stenke, 2007). Additional to the emission database created within SCENIC, a further dataset was calculated, which only include subsonic air traffic (as for S4), but without those aircraft, which are replaced by supersonics in the scenario S5. Figure 7 presents the results for the near surface temperature change caused by the subsonic aircraft which are replaced (S4 – S4-core) and which is caused by the supersonic aircraft replacing the subsonics (S5-S4). Clearly, the impact due to CO_2 is about 3 times larger for supersonics than for subsonics. The total climate impact from supersonics is about 5 times that of the replaced subsonics, which is mainly caused by the water vapour perturbations.

3. ASSESSMENT MODELS FOR MDO

Climate change is a challenge to society and to cope with requires assessment tools which are suitable to evaluate new technological options with respect to their climate impact. Such a tool has been developed within the framework of the EU-Integrated Project HISAC. A brief description of this tool and derived 'climate functions', which can be used for Multi-Disciplinary Optimisation (MDO) will now be given.

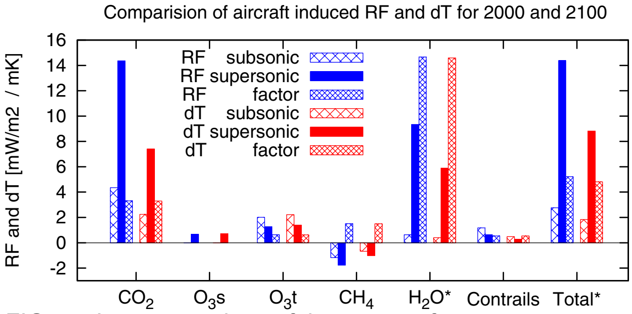


FIG 7. Intercomparison of the near surface temperature change caused by supersonic (filled) aircraft and the respective (replaced) subsonic aircraft (dashed). The third column in each group indicates the factor between the supersonic and subsonic impact.

3.1. Methodology

The assessment tool AirClim is fully described in Grewe and Stenke (2007). It aims at estimating the temporal development of the climate impact of emissions in terms of changes in the globally mean near surface temperature. The approach is based on a linearisation of processes (transport, chemistry, radiation) by applying a detailed state-of the art 3D-climate chemistry model. Emissions of water vapour and nitrogen oxides are released at various points of the atmosphere and their impact simulated by applying a climate chemistry model. These simulations describe the sensitivity of the atmosphere to various emission regions (see sec. 3.2). The simulations result in concentration changes of climate gases and particles, such as water vapour, ozone, methane and contrails. Note that the climate impact of a carbon dioxide emission is independent of the emission region due to its long lifetime (~100 ys.)

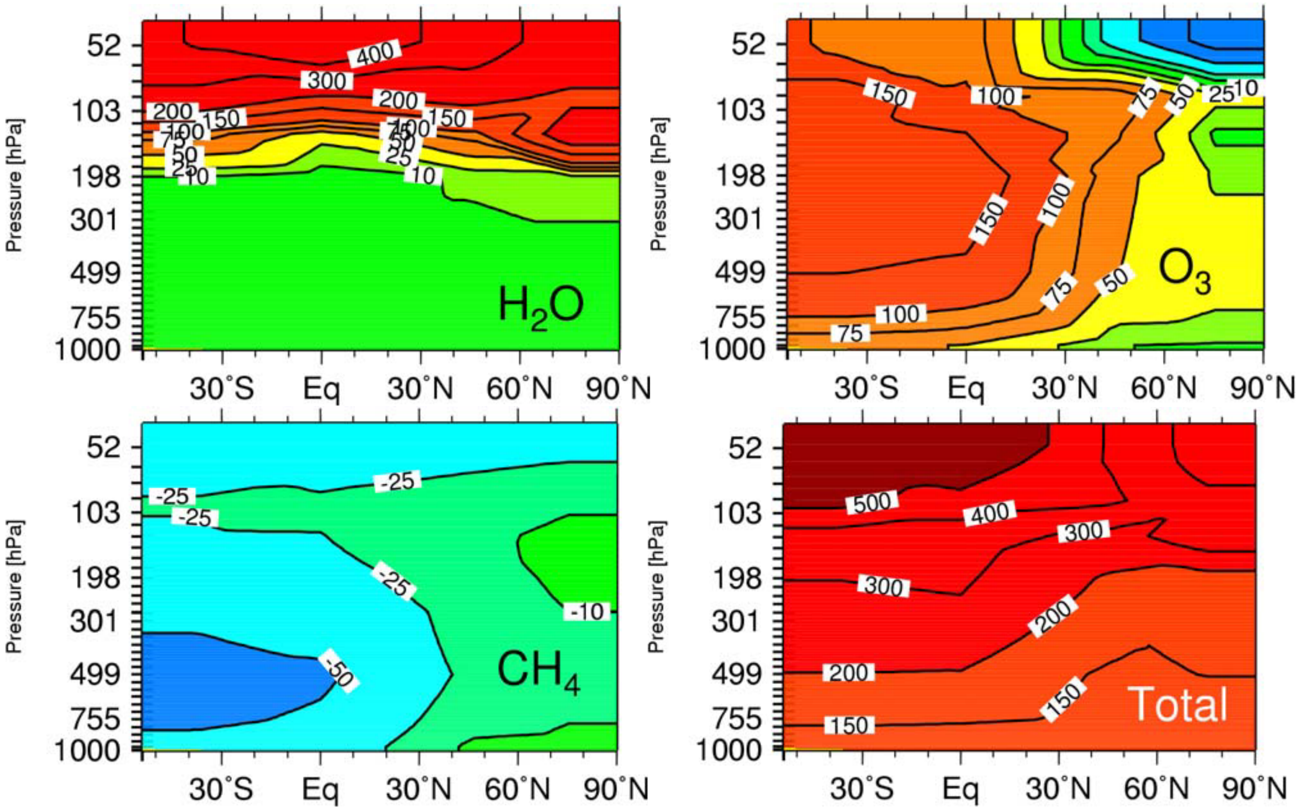


FIG 8. Atmospheric sensitivity in terms of near surface temperature changes [mK] to emissions of water vapour, NO_x (ozone and methane), and the sum of all effects (e.g. including contrails and CO_2). For each region a fuel consumption and NO_2 emission index according to the SCENIC subsonic fleet was taken into account (677 Tg fuel per year and 10.85 g(NO_2) per kg(fuel)).

3.2. Atmospheric sensitivity to emissions

Figure 8 shows the temperature changes caused by unit emissions of H_2O and NO_x. The emission values of the scenario S4 (TAB 1) are taken into account for this investigation. Water vapour has its largest impact on climate change, when emitted in the tropical stratosphere, whereas the ozone impact is largest in tropical tropopause regions. At high and mid northern latitudes a decrease in temperature is found due to large ozone depletion. Generally, the NO_x-methane induced temperature decrease partly compensates for the NO_x-ozone temperature increase. Largest changes are found in the tropical mid troposphere. The total effect (including CO_2 and contrails) is given in the lower right.

3.3. A first approach to include climate change in MDO

The results presented in FIG. 8 can be used to derive a functional relationship between aircraft parameters (here: cruise altitude, fuel consumption) and climate change, which describes the main characteristics. Basically three assumptions have to be made:

1) Only emissions during **supersonic** cruise are considered.
2) Only water vapour and carbon dioxide are considered.
3) 40% of the emissions take place at mid-latitudes; the rest is equally spread over other regions.

Applying assumption 3 to the water vapour results presented in Figure 8 leads to a global water vapour impact profile, which can be fitted with:

(2)

$$\Delta T^{H_2O}(CA,FC) = [-0.925 \times \log_{10}(CA) + 2.14] \times 10^{-9} \times FC$$

with ΔT the near surface temperature change in [mK], *CA*=Cruise Altitude in [hPa] and *FC*=Fuel Consumption in [kg]. The climate impact from CO_2 can be added additionally, which gives

(3)

$$\Delta T^{H_2O+CO_2}(CA,FC) = [-0.925 \times \log_{10}(CA) + 2.31] \times 10^{-9} \times FC$$

Figure 9 shows a visualisation of functions (2) and (3).

4. CONCLUSIONS

Here a way is proposed how to evaluate options for aircraft in terms of environmental impact (chemical composition and climate). The methodology is based on a combination of the near surface temperature change and a change of the stratospheric ozone depletion relative to a base case. The base case has been a mixed fleet of subsonic aircraft and 501 supersonic aircraft with a cruise speed of Mach 2 and a capacity of 250 passengers. For the perturbation scenarios supersonic configurations are taken into account with an increased emission index for NO_2 during supersonic cruise (P2), a doubled fleet size (P3), or which are optimised with respect to a lower cruising speed (P4), an extended range (P5), and a reduced cruise altitude (P6).

The applied approach utilizes a number of models which are stepwise linked. In a first step, a transient emission scenario for total fuel use is developed based on the SCENIC emission data bases for 2025 and 2050 and on the TRADEOFF database for the present. In a second step, concentration changes are calculated for ozone, water vapour and methane employing 4 global atmosphere-chemistry models for the time slice 2050. Contrail coverage changes are calculated based on the E39/C model. The stratospheric adjusted radiative forcing is then calculated by applying a general circulation model and using the output of the atmosphere-chemistry model simulations. Various climate sensitivity parameters are calculated based on a general circulation model coupled to a mixed layer ocean. Utilising a linear response model, the radiative forcing and the climate sensitivity parameter leads to an estimate of the near surface temperature change, allowing for different response time-scales of the chemistry-atmosphere-ocean system. All steps include some uncertainties, which are either determined through the spread of model results, or taken from the literature. These uncertainties are determined for each individual component and then combined to give an overall uncertainty for the combined optimization metric.

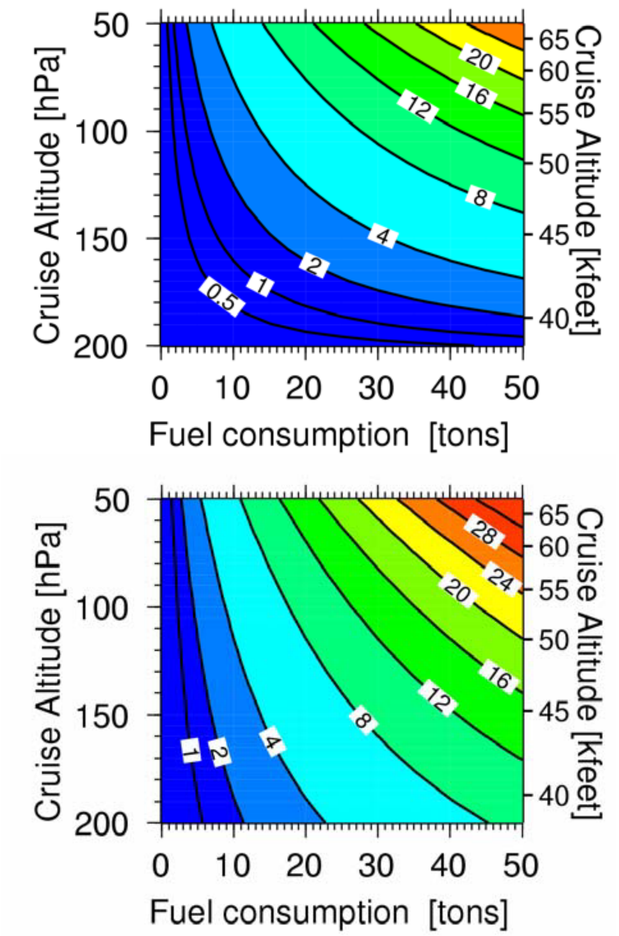


FIG 9. Illustration of the relationship between cruise altitude, fuel consumption and near surface temperature change in [10^{-9}K]. Top: Water vapour emissions only; Bottom: Water vapour and carbon dioxide emissions.

In principle this approach has already been used in the IPCC (1999). However, they concentrated on RF and ozone column changes and did not try to optimize the combined effect.

The results clearly show that, in agreement with previous findings (IPCC, 1999) stratospheric water vapour emissions are by far the most important contributor to climate change with respect to a supersonic fleet. The scenarios P4 (lower cruise speed) and P6 (reduced cruise altitude) minimise the overall environmental impact, mainly because the water vapour impact and ozone depletion are smaller.

Further an efficient assessment tool (AirClim) has been very briefly introduced. It comprises a linearisation of the above described methodology. The atmospheric input data describe the atmosphere's sensitivity to regional emissions. From that a functional relationship has been derived which describes climate impact as a function of aircraft parameters (cruise altitude and fuel consumption).

5. REFERENCES

[1] Fuglestvedt, J., Berntsen, T., Myhre, G., Rypdal, K., and Skeie, R.: Climate forcing from the Transport Sectors, PNAS, submitted, 2007.

[2] Grewe, V., A. Stenke, M. Ponater, R. Sausen, G. Pitari,, D. Iachetti, H. Rogers,, O. Dessens, J. Pyle, I. Isaksen, L. Gulstad, C. Marizy, E. Pascuillo, Climate impact of supersonic air traffic: An approach to optimize a potential future supersonic fleet – Results from the SCENIC EU-project, ACPD, 7, 1-45, 2007.

[3] Grewe, V., A. Stenke, A strategy for climate evaluation of aircraft technology: An efficient climate assessment tool: AirClim. To be submitted to ACPD, 2007.

[4] Sausen, R. and Schumann, U.: Estimates of the climate response to aircraft CO_2 and NO_x emissions scenarios, Clim. Change, 44, 25-58, 2000.

[5] Sausen, R. I. Isaksen, V. Grewe, D. Hauglustaine, D. S. Lee, G. Myhre, M. O. Köhler, G. Pitari, U. Schumann, F. Stordal and C. Zerefos, Aviation Radiative Forcing in 2000: An Update on IPCC (1999), Meteorol. Z. 14, 555-561, 2005.

[6] Schumann, U., Busen, R., and Plohr, M.: Experimental test of the influence of propulsion efficiancy on contrail formation, J. Aircraft, 37, 1083-1087, 2000.

[7] Søvde, O. A., Gauss, M., Isaksen, I.S.A., Pitari, G. and C. Marizy, Aircraft pollution – a futuristic view, Atmos. Chem. Phys., 7, 3621-3632, 2007.

[8] Stenke, A., Grewe, V., and Pechtl, S.: Do supersonic aircraft avoid contrails?, Atmos. Chem. Physc. Disc., 7, in preparation, 2007a.

Acknowledgement

This study has been partly supported by the European Commission through the Integrated Project HISAC and the Network of Excellence ECATS under the 6th Framework Programme. Many thanks to Regina Egelhofer, Technical University Munich and Corinne Marizy, Airbus for providing additional and more detailed datasets of the SCENIC database.