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Reduction of the air traffic's contribution to climate change: A REACT4C case study

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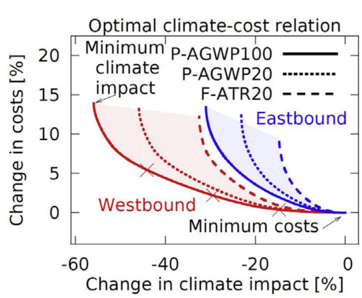
HIGHLIGHTS

- We analysed air traffic re-routing options, which avoid climate sensitive regions.
- A case study for one specific winter day is analysed for trans-Atlantic flights.
- A large potential exists to reduce the air traffic's contribution to climate change by re-routing.
- Small changes in flight trajectories already significantly reduce their climate impact.
- A 25% decrease in the climate impact can be achieved at a 0.5% cost increase.

GRAPHICAL ABSTRACT



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ABSTRACT

Air traffic alters the atmospheric composition and thereby contributes to climate change. Here we investigate the trans-Atlantic air traffic for one specific winter day and analyse, which routing changes were required to achieve a reduction in the air traffic's contribution to climate change. We have applied an atmosphere-chemistry model to calculate so-called five dimensional climate cost functions (CCF), which describe the climate effect of a locally confined emission. The five dimensions result from the emission location (3D), time (1D) and the type of emission (1D; carbon dioxide, water vapour, nitrogen oxides). In other words, carbon dioxide (CO_2), water vapour (H_2O) and nitrogen oxides (NO_x) are emitted in amounts typical for aviation at many confined locations and times and their impacts on climate calculated with the atmosphere-chemistry model. The impact on climate results from direct effects, such as the changes in the concentration of the greenhouse gases CO_2 and H_2O and indirect effects such as contrail cirrus formation and chemical changes of ozone and methane by emissions of NO_x. These climate cost functions are used by a flight planning tool to optimise flight routes with respect to their climate impact and economic costs of these routes. The results for this specific winter day show that large reductions in the air traffic's contribution to climate warming (up to 60%) can be achieved for westbound flights and smaller reductions for eastbound flights (around 25%). Eastbound flights take advantage of the tail winds from the jet stream and hence routings with lower climate impacts have a large fuel

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penalty, whenever they leave the jet stream. Maximum reduction in climate impact increases the economic costs by 10–15%, due to higher fuel consumption, caused by a longer flight distance and lower flight levels. However, with only small changes to the air traffic routings and flight altitudes, climate reductions up to 25% can be achieved by only small changes in economic costs (less than 0.5%).

1. Introduction

Air transportation has an important role in international mobility. Global scheduled air passenger traffic has grown in 2012 by 4.9% and is expected to grow further by up to 6% by 2015 (ICAO, 2013). Air traffic has a significant contribution to anthropogenic climate change (Berntsen and Fuglestvedt, 2008; Lee et al., 2010), which is expected to grow further. The emissions from air traffic, i.e. carbon dioxide, nitrogen oxides, water vapour, carbon monoxide, unburned hydrocarbons, and soot lead to changes in the composition of the atmosphere (Lee et al., 2010), which are relevant for climate change through changes in the greenhouse gas concentrations of carbon dioxide (CO_2), ozone (O_3), water vapour (H_2O), and methane (CH_4) and the formation of contrail-cirrus (Lee et al., 2010; Burkhardt and Kärcher, 2011). The impact of a locally confined air traffic emission shows a large spatial and temporal variability, except for carbon dioxide, because of its long perturbation lifetime. In some regions, emitted NO_x is rapidly washed-out, in others it remains for several weeks in the atmosphere (e.g. Grewe et al., 2014). Formation of persistent contrails occurs in ice-supersaturated regions, only, which also have a large spatial and temporal variability (Spichtinger et al., 2003; Gierens et al., 2004). Nowadays, aircraft trajectories are optimised with respect to time and economic costs (fuel, crew, air traffic control). They avoid hazardous regions, such as thunderstorms and take advantage of tail winds, e.g. from jets streams. Regions in which emissions lead to more pronounced climate change, so-called climate-sensitive regions, are currently not considered in flight planning and air traffic management.

In the present study, we investigate lateral and vertical re-routing options to reduce the impact of air traffic on climate, by avoiding such climate sensitive regions. Since the modelling approach is very complex, we first published the model description, experimental set-up and evaluation (Grewe et al., 2014) and apply exactly this model version in this investigation, which is focussing on a one day case study with a more detailed analysis. A further publication will build hereon and show the impact of different weather situations. Special focus is given here on the relationship between the benefit of re-routing options, i.e. the reduction of climate warming, and the economic costs of these options in terms of fuel costs and crew costs which are the main drivers for today's flight planning. The idea of weather specific re-routing of air traffic for the benefit of climate has been addressed before (Sausen et al., 1994; Mannstein et al., 2005; Schumann et al., 2011; Sridhar et al., 2011, 2013; Zou et al., 2013). However, none of these studies included such a broad range of atmospheric effects, as addressed in this study (contrails, carbon dioxide, ozone, methane, and water vapour) and traffic complexity (complete one day real air traffic sample for a larger region). In this study, the changes in ozone are separated in short term changes caused by NO_x, and long term changes caused by changes in its long-lived precursor methane. The latter is also called primary mode ozone (PMO).

We investigate the trans-Atlantic air traffic between Europe and North America for one specific day. The air traffic and meteorology is presented in Section 2. The methodology of calculating the impact of a local emission on climate is presented in detail in Grewe et al. (2014) and summarised in Sec. 3. The resulting climate cost functions (CCF) are described in Sec. 4. Results concerning the traffic optimisation are discussed in Sec. 5 and an uncertainty discussion is given in Sec. 6. Sec. 7 presents a roadmap of how these results may be implemented in a future air traffic management system.

2. Meteorology and air traffic

We focus on one specific weather situation for winter, and analyse the air traffic routing options for this weather situation for one day. The weather pattern around the main cruise levels (200–300 hPa) is shown in Fig. 1. This weather situation has a trough over the north Atlantic, with a high pressure ridge over Europe (left). It is characterised by a strong zonally-oriented jet stream with wind speeds exceeding 65 m/s in the core of the jet stream around 35°N (right). This pattern is a representative of winter weather type 1 defined by Irvine et al. (2013), and would typically occur on 17 days each winter. Note that Irvine et al. (2013) presented a mean situation for each class, whereas here we are focussing on one specific member of this class, i.e. an individual day. Hence details have to differ, but the main feature, i.e. a strong and zonally jet, is reflected.

The atmospheric model used (see Sec. 3) is a climate model and hence individual simulated days are not linked to real days. However, the same classes of weather patterns with similar frequencies are found in the model compared to re-analysis data. Main meteorological characteristics, such as transport pathways, do not principally differ from observational data. A real day is identified from re-analysis data, where the meteorology matches, with respect to the pressure and wind field, the simulation presented in Fig. 1. For this day, the real air traffic data are used.

This traffic flow includes 391 and 394 flights with 28 and 30 different types of aircraft for eastbound and westbound routes (Table 1). The transport volume and fleet mixture are similar in either direction, though not identical. The flights from Europe to the U.S. start in the (local) morning and the flights from the U.S. start in the (local) afternoon and evening arriving in Europe on the next day. Therefore, this one day air traffic actually spans a little bit more than 24 h.

3. Model description

We use a state of the art climate-chemistry model (EMAC) and traffic simulator (SAAM) to investigate routing options for minimising the air traffic climate impact. The models and the specific set up for this application are described in detail in Grewe et al. (2014). Here, we give a summary, only. The basic idea is to use climate cost functions in an air traffic flow optimisation. The climate cost functions are derived independently from any air traffic and describe the climate impact for a unit emission at a given longitude, latitude, altitude and time.

For the calculation of these climate cost functions, we defined a time-region grid in the North-Atlantic area (from 80°W to 0°W and 30°N to 80°N) on 4 pressure levels around the main flight altitude, which leads to 168 grid points in that area. For each of these time-

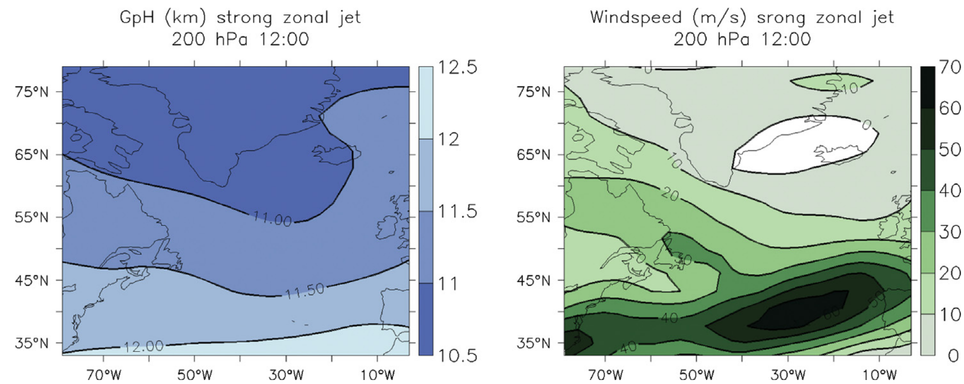

Fig. 1. Geopotential height [km] (left) and windspeed [m/s] (right) at 200 hPa and 12 UTC for the day for which the air traffic optimisation is performed.

region grid points 50 trajectories are started in the corresponding EMAC grid at 3 different times (6, 12, and 18 UTC). A unit emission of CO_2, NO_x, and H_2O is considered at the time-region grid points. The contribution of these emitted species to the atmospheric concentrations is calculated for each trajectory, with respect to NO_y (all active nitrogen species), HNO_3, O_3, H_2O, OH, and CH_4, taking into account wash-out and dry deposition as well as chemical reactions, based on a non-methane hydrocarbon chemistry scheme. In addition, we calculated whether a contrail can form, and processes such as sublimation, sedimentation and contrail spreading are taken into account.

This approach leads to a 4D distribution of trace gases and contrails for which radiation flux changes and eventually radiative forcings are calculated. These are used to calculate different climate metrics, which provide an answer to different climate aspects, or objectives. Here we are focussing on the question: "What would be the short-term and long-term effect on climate, if such a re-routing strategy were applied every day?". Appropriate metrics and associated emission scenarios are given in Table 6 in Grewe et al. (2014) and include the average temperature response with future increasing emissions and the absolute global warming potential with pulse emissions at a 20 year time horizon (F-ATR20 and P-AGWP20) for the short-term climate change aspect. A time horizon of 100 years is taken into account for a long-term climate change aspect (P-AGWP100).

These data describe the specific climate impact in terms of units of the chosen climate metric per emission at the time-region grid points. In a next step they are remapped to the original EMAC grid and combined with EMAC data, such as the potential contrail coverage, forming the climate cost functions.

These climate cost functions are then used in the traffic simulator SAAM, which includes the emission tool AEM, to calculate the emissions along each flight route. The multiplication of the calculated emissions with the climate cost function leads to the total climate impact of the individual flight routes. Alternative routes (21 horizontal and 5 vertical options = 105 routes) are produced for every flight by randomly blocking parts of the air space. Thereby, we obtain 105 options for 785 routes, which gives a total number of 105^{785} possibilities to arrange the trans-Atlantic air traffic of this day, among which the climate optimal and economic optimal air traffic can be determined by linear programming with conflict avoidance (= minimum separation between aircraft) as a constraint.

This modelling approach is a multi-disciplinary approach, which requires some simplifications. They are investigated in more detail in Grewe et al. (2014). Among those is the temporal and horizontal resolution of the climate-cost function, the properties of the simulated contrails, the response in ozone and methane from a NO_x emission, which were found to be adequately represented. A closure experiment showed that the order of the climate impact from the different climate agents is sufficiently well represented with respect to current modelling capabilities. The impact of uncertainties in the calculation of climate-cost functions on the climate optimised air traffic is addressed in sensitivity studies in Section 6.

4. Climate cost functions

Fig. 2 shows the climate cost functions for contrails, ozone, methane and total NO_x effect (=sum of ozone, methane, and PMO) at 200 hPa for 12 UTC. Meteorological fields from Fig. 1 are overlaid, e.g. the location of the low pressure system (thick black line), jet stream (blue dashed line) and the terminator (violet line). Contrails (Fig. 2a) show very different evolution and impacts. In the north-eastern part, e.g. over greenland and East of greenland (see also Supplementary material section S1, regions A and B), contrails form and are transported northward with a lifetime of around 2 h. They are mainly occurring in darkness and lead to a warming. Whereas in the region of the Gulf of Saint Lawrence (region C in Supplementary information, section S1) the contrails show a larger optical thickness and remain at very low solar zenith angles, which lead to a cooling effect, since the negative solar forcing dominates over the positive longwave forcing (see also Meerkötter et al., 1999).

The climate impact of a NO_x emission (Fig. 2d) results from an increase in ozone and a warming effect (Fig. 2b) and a decrease in methane and an associated reduced warming effect (Fig. 2c). The ozone impact (Fig. 2b) is larger in the area of the jet stream and shows a minimum in the location of the low pressure system. Air masses, which are transported towards higher latitudes, e.g. originating from around 30°W and 60°N, are also transported to higher altitudes. This implies a longer atmospheric lifetime of the emitted species NO_x and H_2O, but also a smaller production of ozone, since in that region (lower stratosphere) and time (winter) the chemical reaction rates are low. At lower latitudes (e.g. at 75°W and 60°N), the emitted species are transported to the tropics and experience a large ozone production, though for a short time period, since the nitrogen compounds have a lower residence time, caused by wash-out. Still the higher ozone production dominates and leads to strong warming effects. The range in the ozone induced warming is one order of magnitude in the displayed area (Fig. 2b).

Methane depletion is caused by an increase in the OH concentration, which results from 2 chemical reactions. During an initial period, the reaction of NO with HO_2 leading to NO_2 and OH, results in methane depletion and in a later stage, when the NO_x concentration has dropped and the ozone concentration is still at a higher level, the reaction of $O(^1D)$ (from ozone photolysis) with water

Table 1
Overview on aircraft used for west and eastbound flights.

Aircraft	Number of flights	
	Eastbound	Westbound
A310	6	4
A319	1	–
A330: 200/300	20/32	20/31
A320-200	–	1
A340: 300/600	23/10	25/10
B737	1	–
B747: 100/200/300/400	3/5/–/50	–/7/1/50
B757: 200/300	19/1	18/1
B767: 200/300/400	13/93/6	10/98/5
B777: 200/300	72/2	72/2
C130	–	2
C17	6	1
C5	2	3
C750	1	–
CL60	–	1
DC10	2	2
E135	–	1
F2TH	1	–
F900	–	2
GLEX/F2/F3/F4/F5	–/–/–/2/2	2/1/1/4/1
H25B	1	–
K35R	1	1
LJ35	1	–
MD11	15	17
Total	391	394

vapour leads to two OH radicals. The total NO_x effect on temperature is then positive at lower latitudes and negative at higher latitudes (Fig. 2d). This is in agreement with earlier studies, which showed a stronger ozone induced warming at lower latitudes and roughly a balance between ozone warming and a reduction in methane reduced warming effects at higher latitudes (Grewe and Stenke, 2008).

The results show a broad variability in the temporal evolution of the atmospheric masses of H_2O, NO_x, ozone and methane, caused by the pulse emission at the climate cost function grid box, which are in agreement with earlier studies (for more details see Grewe et al., 2014).

5. Climate optimal air traffic

We have optimised the trans-Atlantic one-day air traffic with respect to different objectives: economic costs, short-term climate impacts (F-ATR20 and P-AGWP20) and long-term climate impacts (P-AGWP100). The results, shown in Fig. 3, are separated for westbound (blue shaded) and eastbound (red shaded) flights, since the impact of meteorology on routing, largely differs depending on the flight direction, as tail and head winds play a large role (e.g. Irvine et al., 2013). We define a reference point which is that air traffic routing with the minimum cost and discuss the economic costs and climate changes from traffic changes in relation to this reference point. The climate optimised air traffic leads to a maximum reduction of the climate impact in the range of around 25%–60% associated with an increase in economic costs around 15%.

We find a clear difference between eastbound and westbound flights. Eastbound routes benefit from the tail winds of the jet stream. Each re-routing option for eastbound routes which leaves the jet stream has a significant increase in fuel consumption. In contrast, westbound flights and any re-routing option both avoid

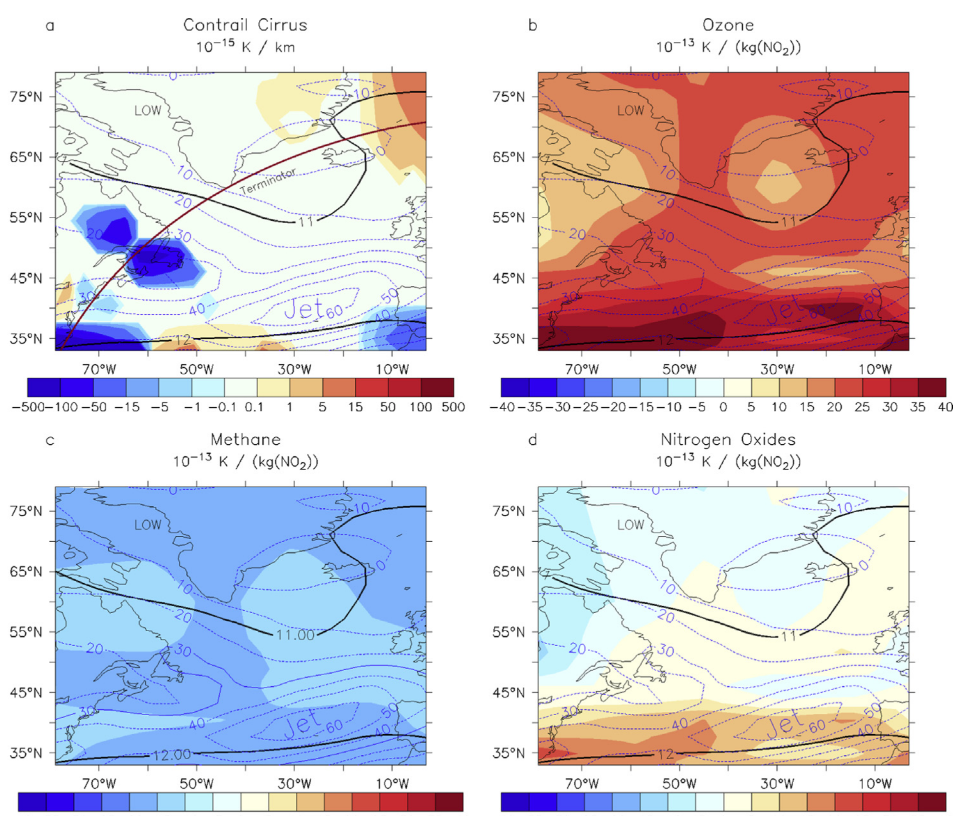

Fig. 2. Climate cost functions for the metric F-ATR20 at 200 hPa and 12 UTC (as in Fig. 1), i.e. 20 year mean near-surface temperature change induced by an aircraft flying. a) Contrails (AiC) in [10^{-15}K/km] b) to d) Ozone, Methane and total NO_x, respectively in [10^{-13}K/kg(NO_2)]. The meteorology from Fig. 1 is overlaid, i.e. black isolines show the geo-potential height and the blue dashed lines the location of the jet stream. The terminator is indicated by a violet line.

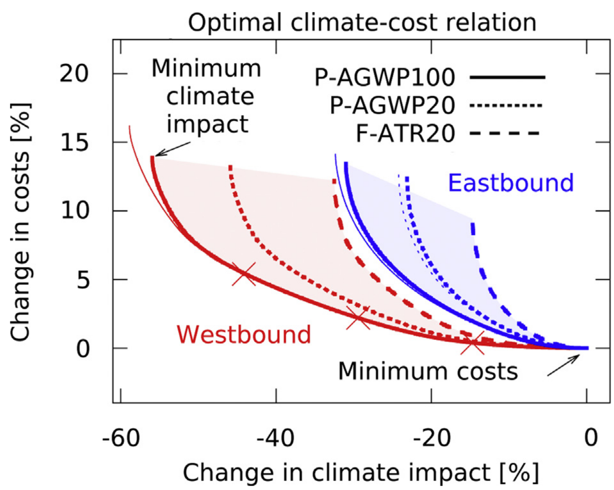

Fig. 3. Relation of economic costs changes and climate impact changes for the one-day trans-Atlantic air traffic. Westbound and eastbound flights are in red and blue, respectively. Three different climate metrics are used: P-AGWP100 (thick solid lines), P-AGWP20 (thick dotted lines), and F-ATR20 (thick dashed line). Thin lines give results using more (125) alternative options in the optimisation (see text for more details). Crosses mark the 25%, 50% and 75% reduction of maximum climate impact reduction, discussed further in the text.

head winds. Hence the difference in fuel consumption between each westbound re-routing option and the reference (minimum cost) flight is less compared to the eastbound flights. In addition, any increase in fuel consumption also implies an increase in NO_x emissions. Therefore, for this specific meteorological situation, the westbound air traffic has more re-routing possibilities avoiding non-CO_2 warming effects with only small increases in fuel consumption and compensating CO_2 induced warming, compared to eastbound air traffic.

For each metric and flight direction, the Pareto front (optimal relation between climate change and costs) is included in Fig. 3. Starting from the economic best flights (lower right), we change successively re-routing flight options, starting with the most promising, i.e. largest climate reductions at lowest cost increase. Already large reductions in the climate impact of up to 25% can be achieved by only small increases in economic costs of less than 0.5% (red solid line).

For long-term climate impacts (time horizon of 100 years; (solid lines)) the reduction is larger than for short-term climate impacts (non-solid lines), simply because the reduced warming by methane leads to both a smaller reference value and a larger reduction potential. Fig. 4 shows the relative importance of the individual contributions normalised to the respective contrails (AiC = Aircraft induced cloudiness) values. Clearly, all metrics as well as eastbound and westbound show a similar pattern. Ozone values (blue) are generally slightly larger than the respective contrail values (green). Carbon dioxide (red) is more important for long-term effects (P-AGWP100) than for short-term effects (P-AGWP20 and F-ATR20). Methane effects (magenta) are also more important for long-term than for short-term objectives, with the lowest impact for F-ATR20, caused by the different underlying future emission scenario. The difference in the lifetime of ozone and methane leads to different total NO_x effects (light blue), which are negative (reduced warming, i.e. net-cooling) for the metric focussing on long-term effects compared to positive (warming) effects for the short-term. Generally the relation between the individual components is in good agreement with earlier studies, e.g. Fuglestvedt et al. (2010).

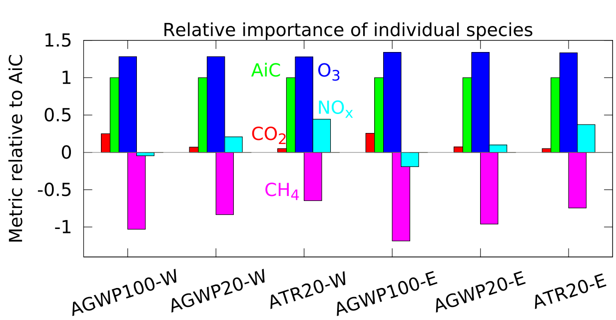

Fig. 4. Relative importance of individual species for a reduction of the climate impact from air traffic. For each metric and direction (see also Fig. 3) the change in the metric value for CO_2 (red), contrails (AiC, green), ozone (blue), methane (magenta), and total NO_x (O_3 + CH_4 + PMO, cyan) are given relative to the respective value for contrails (hence contrails are always 1).

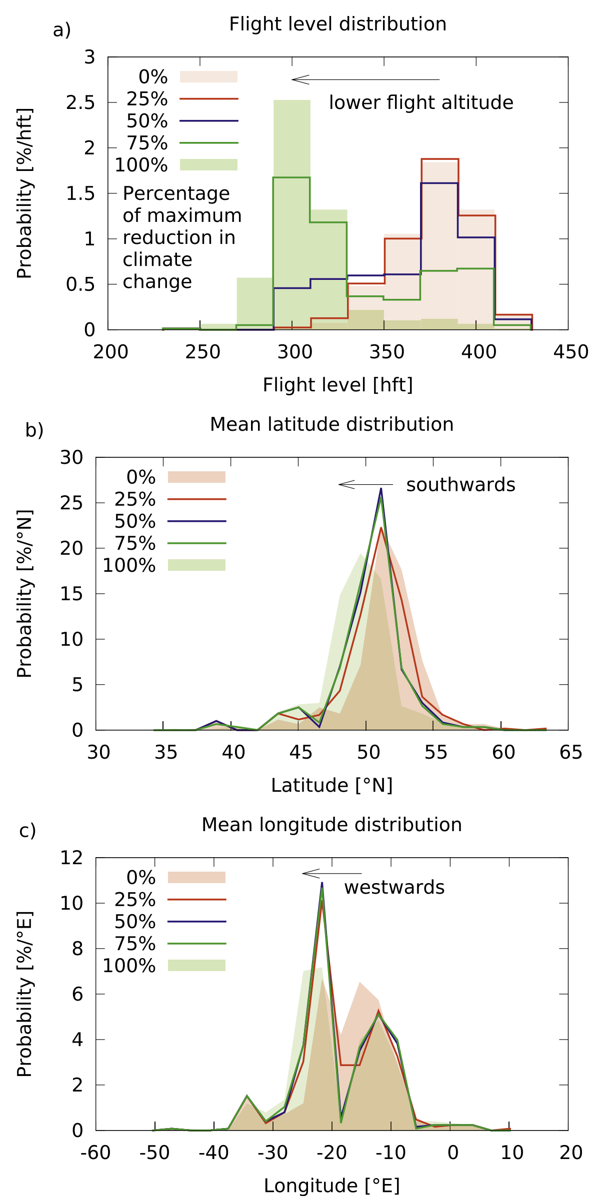

Fig. 5. Change of the probability density function of air traffic characteristics along the Pareto front for westbound air traffic and P-AGWP100. a) flight level, b) mean latitude and c) mean longitude. See also Supplementary information (Fig. S3) for the interpretation of mean longitudes and latitudes.

It is important to note here that we are only regarding a small, though important subset of the annual world's air traffic which takes place in winter at relatively high latitudes. The results cannot be taken for the whole air traffic, but only for this specific case study. As already shown in Grewe and Stenke (2008) this region is characterised by an effect of ozone and methane from NO_x emissions, which are both equally important, but of opposite sign. As a result the net NO_x effect might be negative, whereas at more southern latitudes the positive (warming) ozone effect is dominating.

Fig. 5 shows the air traffic changes (westbound flights) along the Pareto front (see also Supplementary material Fig. S3 for a full presentation of all changes of the probability density functions along the Pareto-front). Changes are similar for all metrics, so we are concentrating here on P-AGWP100. Air traffic with minimum economic costs peaks at a flight level of 380 hft (Fig. 5a; red), whereas climate optimal air traffic shows a peak much lower at 300 hft. However, only minor changes of the flight level distribution are necessary to already obtain 25% of the maximum climate impact reduction (red line vs. red area). The changes in flight level distribution are even moderate between a climate impact reduction of 25% and 50% of the maximum (red and blue line). The barycenters of the flight trajectories move southwards and westwards (Fig. 5b,c), which means that the aircraft starting from Europe shift their route first southwards compared to the best economic solution and countersteer in western parts of the flights, i.e. closer to the U.S. (Fig. 6). See Supplementary material (Fig. S4) for more explanations on the interpretation of the mean longitude and latitude of trajectories. Similar to the flight altitude, only minor changes in the horizontal routings are necessary to achieve 25% of the maximum possible climate impact reduction.

The routing changes for climate impact minimisation lead to an increase in fuel use (Fig. 7a), larger flight distance (Fig. 7b), and longer travel times (Fig. 7c). Mean values of the changes are given in Table 2. A little bit more than half of the flights are altered to obtain a 25% reduction of the maximum possible climate change reduction. The mean flight level and duration is changed only marginally. The mean flight time is even reduced and the mean barycentre of the trajectories is shifted by 2°N and 2°W.

The probability density functions (pdf) of fuel use, distance and duration are very different in shape, e.g. the fuel use has a clear peak at around 40 t, whereas the pdf of the route distance show a broad peak between 5.5 and 7.5 10^3 km, almost equally distributed. Changes in the pdf for fuel (Fig. 7a) and duration (Fig. 7c) show a shift to larger values. The pdf of the flown distances has a different behaviour. The number of flights at around 5000 km is reduced and flights between 5500 and 7500 km are increased.

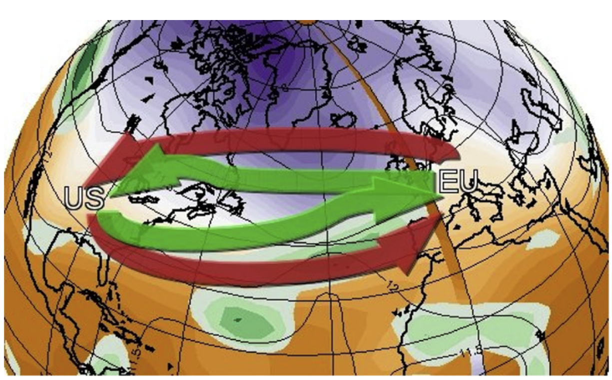

Fig. 6. Sketch of the air traffic flow pattern for the economical best solution (red arrows) and climate best solution (green arrows) for the metric P-AGWP100.

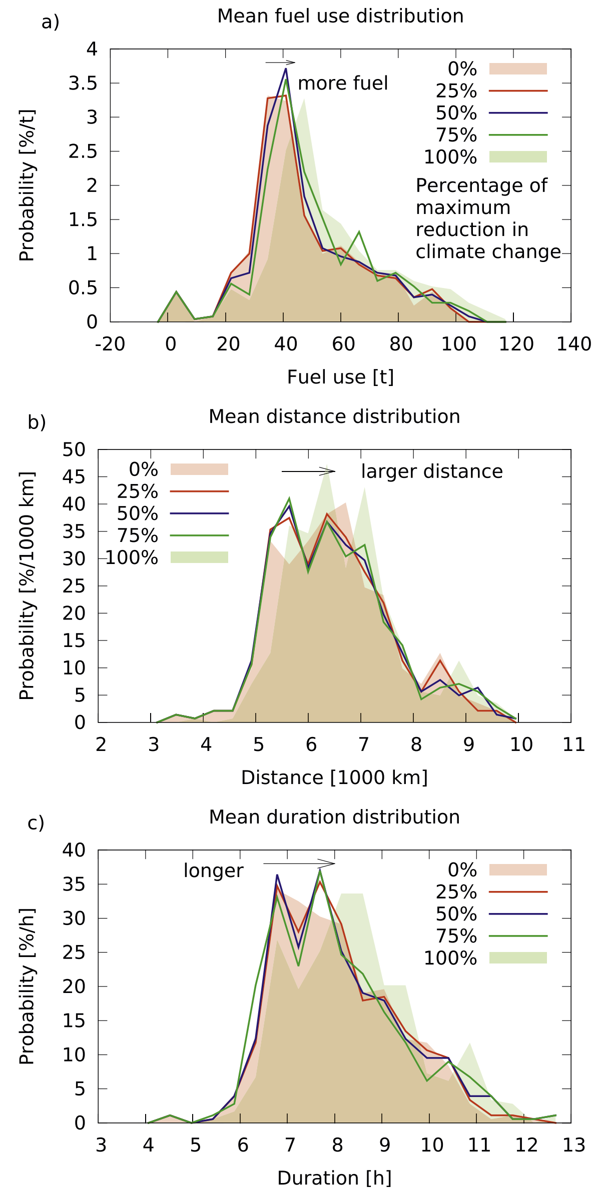

Fig. 7. Change of the probability density function of air traffic characteristics along the Pareto front for westbound air traffic and P-AGWP100. a) fuel use b) distance c) time.

The main driver for the changes in the air traffic routing are contrails and the impacts from nitrogen oxides (Fig. 8). Table 2 gives an overview on mean properties of the air traffic at different locations on the Parteo-front. While contrails show a very linear reduction potential when achieving 25%, 50%, 75% and 100% of the maximum climate impact reduction, the NO_x induced reduction potential increases overproportionally (Table 2). And hence contrail impacts are dominating over the NO_x impacts up to a climate impact reduction of 50%, whereas for the rest, i.e. up to the total (100%) climate impact reduction, the NO_x impacts are getting more important. The NO_x effects are basically due to larger reduction in warming from methane depletion compared to ozone. The direct fuel use induced CO_2 effects and even more the water vapour impacts are small, compared to NO_x and contrails.

For eastbound flights (Table 3), their barycenters (see Fig. S4), are shifted northwards, eastwards, and downwards to minimise their climate impact. Similar to the westbound flights, contrails are more important than NO_x effects when optimising for 25% and 50%

Table 2
Mean values of the air traffic for different degrees of climate reduction for P-AGWP100, westbound flights. The climate impact for NO_x includes ozone, methane and PMO.

Parameter	Units	Climate impact reduction relative to optimum				
		0%	25%	50%	75%	100%
Number of changed flights	–	0	230	321	383	391
Flight level	hft	380	379	364	336	311
Distance	km	6704	6646	6657	6676	6957
Duration	h	8.24	8.27	8.31	8.29	8.83
Mean latitude	°N	52.1	51.4	51.0	50.8	49.9
Mean longitude	°W	15.8	16.9	17.0	17.1	17.6
Climate impact contrails	nW/m^2	55	50	44	39	35
Climate impact ozone	nW/m^2	70	70	71	76	86
Climate impact methane	nW/m^2	−57	−59	−64	−72	−85
Climate impact NO_x	nW/m^2	−3	−6	−11	−16	−24
Climate impact H_2O	nW/m^2	0.07	0.07	0.07	0.08	0.09
Climate impact CO_2	nW/m^2	13.7	13.7	14.0	14.6	16.3

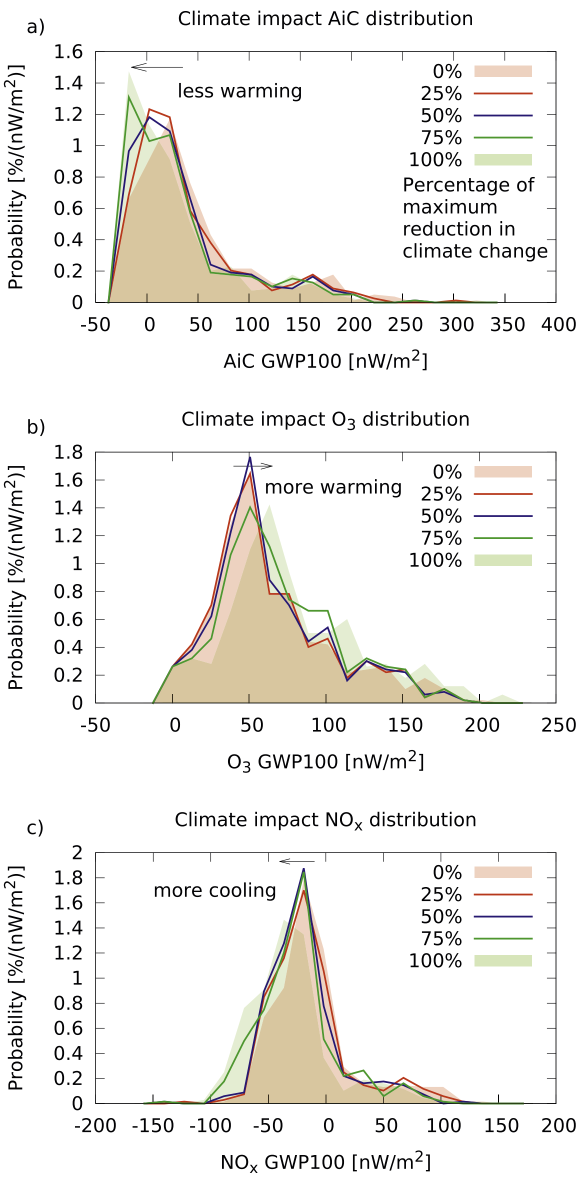

Fig. 8. Change of the probability density function of air traffic characteristics along the Pareto front for westbound air traffic and P-AGWP100. a) Contrail b) ozone c) NO_x.

of the maximal possible reduction in climate change. On the other hand, the reduced warming effects from methane depletion are more dominating for larger reductions in climate change.

In order to investigate which species is driving the optimisation, we define the contribution $r(S,i)$ to the optimisation of individual species S at the optimisation target i ($i = 0, \ldots, 100\%$ of the maximum possible reduction):

$$r(S,i) = \frac{M(S,i) - CI(0\%)}{CI(100\%) - CI(0\%)}, \tag{1}$$

where $M(S,i)$ is the climate impact resulting from species S and measured by the metric $M(S,i)$ and CI the total climate impact of all species, e.g. $CI(100\%) = \sum_{\text{all} S} M(S, 100\%)$. Fig. 9 shows that generally, the role of the individual atmospheric components during the optimisation is similar for all metrics and flight directions, though with a slightly different weighting between eastbound and westbound flights. During the first phase contrails are the most important driver for the climate impact minimisation, whereas NO_x effects, driven by methane reduction (reduced warming), are important to achieve a maximum climate impact reduction.

6. Sensitivity of routing changes to uncertainties in the climate-cost functions

The calculation of the climate optimised air traffic depends on both the calculated climate cost functions and the optimisation approach. To investigate the sensitivity of the routing and the possible climate impact reduction to uncertainties in the climate cost function calculations, we concentrate on the westbound air traffic and the GWP100 metric, since the optimisation possibilities are largest for this case and hence the uncertainties have the largest impact.

Table 4 gives an overview on the sensitivity studies. Basically, we alter the climate-cost functions within uncertainty ranges and repeat the air traffic optimisation to quantify the impact. One important uncertainty is the relative importance of the individual components CO_2, contrails, ozone and methane. We address this aspect by two sensitivity studies: "ContMax" and "NO_xMax", in which the constants $5\,10^{-12}$ $W/m^2/km$ and $7.5\,10^{-11}$ $W/m^2/kg(NO_2)$ are added to the contrail and NO_x (here CH_4) climate cost functions, respectively. This addition leads to roughly 30 and 60 nW/m^2/flight for contrails and NO_x (compare Table 2). This offset roughly represents the range of uncertainty as characterised by Lee et al. (2009). A second set of sensitivity studies addresses the question, whether the variability of the atmospheric responses are correctly represented. Here we multiply the contrail and ozone climate cost functions by 2 ("Cont*2" and "O_3*2"), respectively. This leads to a broader frequency distribution of the individual climate impacts.

Fig. 10 shows the results of the sensitivity studies. The different weighting of the contrail and NO_x climate impacts in the sensitivity studies "ContMax" and "NO_xMax" shows a large reduction in the relative climate change reduction potential (Fig. 10 top, green and blue line), however, this results largely from the change in the reference value for the climate impact of the economically optimised routes (bottom). The absolute changes and also the changes in flight pattern are very similar.

The sensitivity studies on the variability of contrails and ozone impacts ("Cont*2" and "O_3*2") show a much larger climate impact reduction for contrails compared to the base case, and in contrast a smaller reduction potential for the ozone sensitivity experiment. The shape of the Pareto front changes significantly for both NO_x sensitivity experiments. There are some climate impact reductions possible for low economic costs, but then the cost–benefit ratio is

Table 3
As Table 2, but for eastbound flights.

Parameter	Units	Climate impact reduction relative to optimum				
		0%	25%	50%	75%	100%
Number of changed flights	–	0	207	307	354	390
Flight level	hft	389	387	376	359	324
Distance	km	6768	6757	6739	6756	6981
Duration	h	7.26	7.29	7.32	7.39	7.72
Mean latitude	°N	49.0	49.1	49.3	49.7	50.0
Mean longitude	°W	18.2	18.0	18.0	−18.1	−17.8
Climate impact contrails	nW/m^2	47	45	43	42	42
Climate impact ozone	nW/m^2	63	62	64	66	73
Climate impact methane	nW/m^2	−56	−57	−60	−64	−74
Climate impact NO_x	nW/m^2	−9	−11	−13	−16	−22
Climate impact H_2O	nW/m^2	0.06	0.06	0.06	0.06	0.07
Climate impact CO_2	nW/m^2	12.0	12.1	12.3	12.8	14.0

getting worse abruptly, whereas for the other scenarios the changes are much smoother.

Although the relative and less the absolute numbers show a sensitivity to uncertainties in the climate cost functions, the driving parameters are very similar to the base case (for the base case see Fig. 9, for sensitivities see Supplementary material Fig. S5).

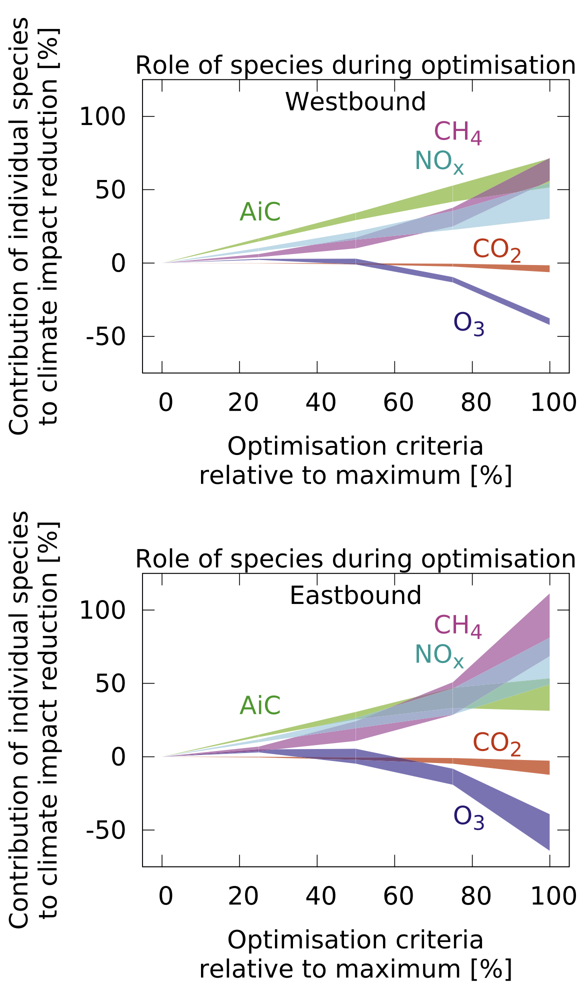

Fig. 9. Contribution in [%] of CO_2 (red), contrails (AiC, green), ozone (blue), methane (magenta), and total NO_x (=O_3 + CH_4 + PMO) to the climate warming reduction by re-routing the North-Atlantic air traffic. The area between the minimum and maximum values for all metrics is highlighted.

In contrast to the impact of uncertainties in the climate cost functions, the uncertainties in the optimisation are small. Variations in the route options for 85, 105 and 125 options show only small changes (for the comparison 105 to 125 see Fig. 3 thin lines vs. thick lines). Also the conflict avoidance is not limiting the results (crosses in Fig. 10), since obviously the air space over the North Atlantic is not congested.

As a last test, we investigate whether it is sufficient to optimise for contrails or for NO_x, only (Fig. 10, black lines). Both optimisations show a general agreement in the relation between costs and climate impact reduction. Though the optimisation with respect to the climate impact of NO_x emissions only (dashed black line) is deviating from the optimisation with respect to the total climate impact. However the optimisation for 80% or less of the maximum possible climate reduction is agreeing between the base case and these two sensitivities.

7. Discussion on implementation

In the previous sections, we have shown that there is a large potential to reduce the air traffic's contribution to climate change by re-routing options, based on a one winter day analysis. These results are in broad agreement with previous studies (Schumann et al., 2011; Sridhar et al., 2011; Zou et al., 2013). Schumann et al. (2011) applied vertical re-routing strategies for contrail avoidance and concluded that "The reduced warming (or enhanced cooling) by contrails may balance at least part of the CO_2 induced warming by aviation". Sridhar et al. (2011) applied vertical and horizontal re-routings for air traffic for 12 U.S. city pairs and found a 70% decrease of the time aircraft spent in regions where contrails can form at an increase of costs of 2%. Zou et al. (2013) showed for a scenario with large costs associated to contrail induced warming that an increase in costs by 1% is necessary to almost avoid all potential contrail forming regions. Hence, these studies showed that only small changes in flight levels, which imply small changes of costs in the order of 1–4% may, lead to substantial changes in the climate impact from aviation, which is in agreement with our findings.

Since the results were very robust in terms of dependence from the chosen metric and in terms of the role of individual components, the question arises whether the approach can be implemented in an air traffic planning tool right away. Basically, reliable climate cost functions as a part of the meteorological weather forecast have to be provided to the air traffic management. This immediately raises two questions: "Are we already in the position to provide reliable climate cost functions?", and if so, "What would be the airline's benefit to actually take advantage of the climate impact reducing re-routing strategies?".

The calculation of the climate cost functions would be a forecast within a forecast: the forecast of the impact of an emission, which takes place in the future, i.e. within tomorrow's weather forecast. For contrails, this forecast is in the order of a day, but for chemistry we used a 3 months forecast. In a "model world", like in our study, where we know the model's future perfectly well, this is not a problem. However for an implementation, we would need to have a good idea on the long-term (months) weather forecast of the real world, which is obviously not available.

Hence, two steps are necessary to overcome this dilemma. Based on model predictions a reliable statistical estimate of the climate impact could be established. Figs. 1 and 2 suggest that this should be in principle possible, since, e.g. the NO_x response between 0 and $5\ 10^{-13}$ K/kg(NO_2) is located in the area where the geopotential height is between 11.0 and 11.5 km (Fig. 2d) and it is large in the jet stream area. Hence a clear connection between the meteorology and the climate cost functions is given. To establish this correlation, more climate cost functions for more weather patterns have to be

Table 4
Overview on the sensitivity experiments.

Name	Objective	Procedure
Uncertainty in the ratio in the impact of climate agents:		
ContMax	What if contrail effects are systematically underestimated?	Add a constant (5 10^{-12} W/m^2/km) to contrail CCF.
NO_xMax	What if NO_x effects are systematically underestimated? (E.g. overestimation of the methane depletion)	Add a constant (7.5 10^{-11} W/m^2/kg(NO_2)) to CH_4 CCFs
Uncertainty in the calculation of individual CCFs:		
Cont*2	What if the spread in contrail results is underestimated?	Multiply contrail CCF by 2
O_3*2	What if the spread in ozone results is underestimated?	Multiply O_3 CCF by 2
Uncertainty in optimisation:		
Routes	Is the optimisation converging?	80, 105, 125 route options
Conflicts	Is conflict avoidance limiting the results	Conflict optimisation along the Pareto front
ContOnly	Is it sufficient to regard contrails, only?	Regard contrail and CO_2 CCF in optimisation, only
NO_xOnly	Is it sufficient to regard NO_x, only?	Regard NO_x and CO_2 CCF in optimisation, only

calculated. And to ensure reliability, their correctness has to be evaluated by measurements, e.g. for contrails, or multi-model forecasts in the case of chemical impacts. Note that this correlation can then serve as a basis for a weather classification with respect to the impact, i.e. with respect to the climate-cost functions.

The second step is the evaluation of the impact of the re-routing strategy. In very rare cases this could be done with actual measurements. Alternatively, a chemistry-atmosphere model, which includes an air traffic planning tool can be used to test the re-routing strategies.

8. Summary

We have performed an optimisation of the trans-Atlantic air traffic (around 390 flights in either direction) with respect to the air traffic's contribution to climate change. The results are based on a state-of-the art atmosphere-chemistry model EMAC and Eurocontrol's air traffic model SAAM. First, we calculated 5D climate cost functions, which describe the climate impact of a locally confined emission (=3D) at a given time (=1D) on the climate impact induced by emissions (=1D) of carbon dioxide, water vapour, and nitrogen oxides, which affect various climate agents, such as contrail-cirrus, ozone, methane, ozone changes from the induced methane changes, water vapour, and carbon dioxide. The weather situation was characterised by a zonally-oriented jet.

For this one winter day, we found that a reduction of the climate impact of up to 60% for westbound and 35% for eastbound traffic can be achieved with an increase in economic costs due to fuel increase and crew time increases of around 10%–15%. However, a 25% reduction of the climate impact can be already achieved with only small changes in the air traffic routing and economic costs increases by less than 0.5%. The driving parameter is the reduction of the climate warming by contrails. Note that these results are only referring to this specific weather situation. A study on more representative winter and summer weather situations which will form the basis for an analysis of an extended period, is under preparation.

We have investigated the impact of uncertainties in the climate cost function and in the optimisation on the climate impact reduction potential. We found that although extreme changes were superimposed to the contrails and NO_x climate cost functions, the optimal routing gives similar results, though the reduction potentials differ.

This study clearly shows for the first time that a large potential for a reduction of the air traffic impact on climate exists, taking into account all major air traffic related climate agents. This can be achieved by only minor changes of the aircraft trajectories. The implementation is still some steps ahead, but – as we have indicated – feasible.

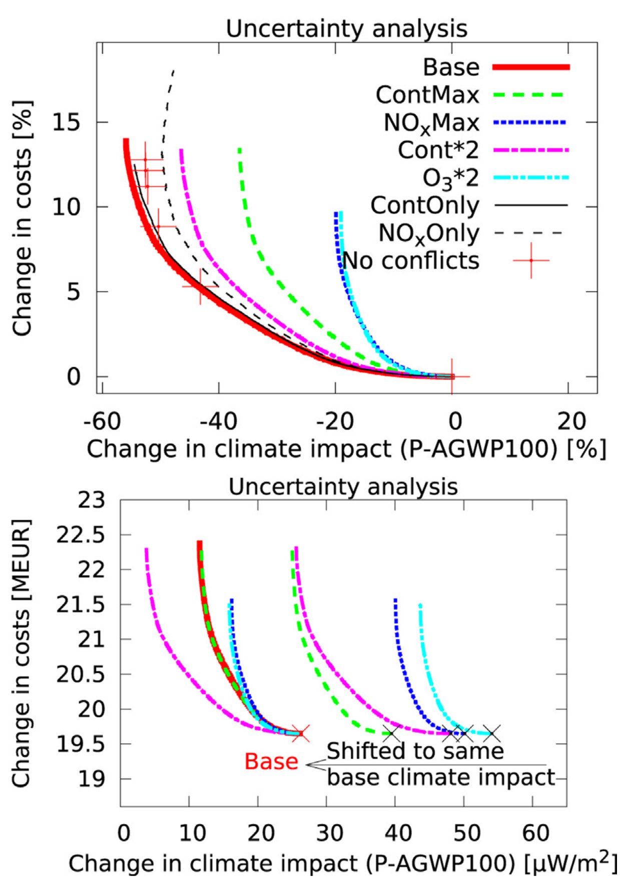

Fig. 10. Pareto front for westbound air traffic P-AGWP100 (analogously to Fig. 3) for various sensitivity analyses (see Table 4). Top: relative numbers in [%]. Bottom: Absolute changes in [MEUR] and [μW m^{-2}].

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2014.05.059.

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