Meteorologische Zeitschrift, PrePub DOI 10.1127/metz/2017/0763

The Implications of Intermediate Stop Operations on Aviation Emissions and Climate

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(Manuscript received December 15, 2015; in revised form August 5, 2016; accepted November 15, 2016)

Abstract

Among the various transport modes aviation's impact on climate change deserves special attention. Due to typical flight altitudes in the upper troposphere and above, the effect of aircraft engine emissions like e.g. water vapour, nitrogen oxides and aerosols on radiative forcing agents is substantial. The projected doubling of aircraft movements in the next 15 years will lead to an increase of aviation's impact on climate and requires immediate mitigation options. Besides technological measures also new operational strategies are widely discussed; one of these concepts which has been subject of several studies in the past is Intermediate Stop Operations (ISO). It is based on the idea to reduce the stage length of flights by performing one or more intermediate landings during a mission. Here, we analyse the ISO concept by combining different models, which include a realistic traffic simulation taking into account operational constraints and ambient conditions, like e.g. wind, the calculation of engine emissions and the integration of a climate response model. We analyse the ISO concept for today's worldwide aircraft fleet, including its influence on global emissions distributions as well as the impact on climate change by taking into account CO_2 and non-CO_2 effects, arising from contrail-cirrus, water vapour and nitrogen oxide emissions. We show in agreement with earlier findings that due to shorter flight distances the amount of fuel burnt over the mission can be reduced by roughly 5 % on average globally. For the first time, we quantify the climate impact of ISO, where the flight trajectory is optimised for fuel use and the aircraft is not redesigned for the ISO procedure. We find an increased warming effect, which arises from nitrogen oxide and water vapour emissions, which are released at higher cruise altitudes and which over-compensate reduced warming effects from CO_2 and contrail-cirrus. However, we expect a climate impact reduction for ISO even with existing aircraft, avoiding the higher flight altitude in the first flight segment and hence reducing the fuel savings. Thus, climate impact benefits could be achieved if lower fuel savings were acceptable. Moreover, this negative climate impact is found for the particular case of introducing ISO using the current wide-body fleet. It does not necessarily apply to the adoption of ISO using aircraft redesigned for a shorter range.

Keywords: Intermediate Stop Operations, Staging, emission inventory, climate assessment, operational concept, mitigation strategies, system-wide analysis

1 Introduction

As aircraft most of the time cruise at high altitudes in the upper troposphere and lower stratosphere, the effect of gaseous emissions from aviation on radiative forcing agents is substantial (Lee et al., 2010; Brasseur et al., 2016). While the effects of CO_2 emission on the climate is generally independent of the emission locus, the effects of non-CO_2 emissions are depending on the weather situation (Grewe et al., 2014) as well as on the cruise altitude (e.g. Gauss et al., 2006; Frömming et al., 2012). Emitted nitrogen oxides produce ozone; the higher aircraft emit NO_x, the larger is its atmospheric residence time and the more ozone develops (Grewe et al., 2002; Søvde et al., 2014). Contrails form when the exhaust air gets, during the mixing with the environment, saturated with respect to water and they persist when the air is ice-supersaturated (e.g. Schumann, 1996). The number of aircraft movements is expected to double in the next 15 years causing aviation's impact on climate to increase further (Airbus, 2014). To limit these effects and to enable a sustainable development of aviation, immediate mitigation options are required. Such mitigation options include technological measures like e.g. new combustion technologies, regulatory measures, but also new operational strategies, which change the way aircraft are operated (e.g. Maynard et al., 2015). Among the operational measures that have been discussed recently are general cruise altitude changes, i.e. flying at lower cruise altitudes (Frömming et al., 2012; Koch, 2013), selective closure of airspaces (Niklass et al., 2015), changing horizontal flight tracks or optimizing the entire trajectory with respect to the expected climate impact (e.g. Grewe et al., 2014; Lührs et al., 2016). These studies have shown that the options

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Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

can reduce the climate impact of flight operations significantly for only comparably small cost penalties. Another such concept, which is often referred to as Intermediate Stop Operations (ISO), suggests that aircraft operators conduct intermediate landings during a mission to reduce the stage length of flights. By refueling the aircraft at a stopover location the amount of fuel burnt over the entire mission can be reduced, as some fuel necessary to transport the remaining fuel over a longer distance can be omitted.

The ISO concept has been subject of some studies in the past, ranging from generic analyses of single missions based on aircraft design methods to investigations on fleet as well as global level. The focus of these studies was mainly to evaluate the potential fuel savings that can be gained by the concept, but partly the authors also looked into the effects on flight times, costs (both single flight operating costs and lifecycle costs) and safety. In some studies it was found that fuel savings are in the order of 13–23 % (the longer the mission, the more fuel could be saved) for missions with a single stopover if aircraft are used that are optimized for shorter ranges (Martinez-Val et al., 2011; Lammering et al., 2011; Langhans et al., 2010; Creemers and Slingerland, 2007). These findings were mainly obtained from payload-range efficiency considerations that have been derived from aircraft design relationships as provided by text books. Similar analyses have been done with current aircraft; here it was found that 5–15 % fuel can be saved depending on the aircraft type and mission length (Poll, 2011; Lammering et al., 2011; Langhans et al., 2010; Creemers and Slingerland, 2007). For these analyses it was assumed that stopover airports were ideally located in the middle of the route, so no real flight and airport networks were considered in these studies (generic mission level). However, some authors also considered real-world conditions; these so-called fleet and global level assessments have been conducted by Poll (2011); Langhans et al. (2010); Green (2005); Linke et al. (2011). E.g., assuming a real geographical distribution of possible intermediate airports for flights operated by Boeing 777 or Airbus A330 Langhans et al. (2010) and Linke et al. (2011) found 10–11 % fuel savings globally if the aircraft is redesigned for 3000 NM (roughly 5600 km). The aircraft redesign was done using NASA's software for preliminary aircraft design called FLOPS (Flight Optimization System). The design range was varied while other design parameters (like e.g. passenger capacity) were kept constant. By analysing the ISO opportunities of the different redesigns in the real flight network it was found that the optimum design range for a new mid-range aircraft optimized for ISO is approximately 3000 NM.

In addition to the positive implications of the ISO concept on fuel consumption and operating costs many authors infer that the concept may consequently reduce the environmental impact of aviation. With regard to the CO_2 footprint this conclusion is valid without further ado, for a sound understanding of the impact of the concept's non-CO_2 emissions on the climate, however, a detailed analysis of the changes of quantities and distribution of individual pollutant species is necessary. Creemers and Slingerland (2007) have estimated a global warming potential reduction of 13 % by ISO with optimized aircraft using a simplified method. For these findings it was assumed that flight altitudes of the redesigned aircraft will slightly increase and that the impact of CO_2, NO_x and H_2O emissions of one kilogram fuel can be modeled as a function of altitude. As stated above, system-wide studies taking real-world air traffic and route networks into account have been performed with a focus on the global fuel saving potential only. A comprehensive study of the global impact of ISO on the environment, i.e. emissions and climate, has not been done so far. That is the focus of this research.

This paper presents a system-wide analysis of the short-term environmental impact of Intermediate Stop Operations. Due to the global character of the study small-scale effects like changes of the local air quality (LAQ) at airports are not considered. The environmental impact is quantified by the amount and the distribution of gaseous engine emissions as well as their effect on climate given as Average Temperature Response (ATR). It is assumed that ISO are carried out with the current world-wide aircraft fleet in a real flight and airport network. All aircraft types and missions that potentially benefit from ISO are considered and realistic operational influences, including wind, are taken into account. By analysing previous emission inventories it can be shown that the selected set of flights account for approximately 28 % of the fuel consumption of the global scheduled air traffic and a similar share of the relevant gaseous emissions like CO_2, H_2O and NO_x. Introducing ISO on these flights thus may have a significant effect on aviation's fuel consumption and emissions. The applied models are described in detail in Section 2 and the simulation set-up is given in Section 3. Results are presented in Section 4 before they are discussed with respect to the model assumptions in Section 5.

2 Methodology

A modeling system was developed that allows for the assessment of operational concepts, like e.g. ISO, with respect to their impact on global emissions and climate. As depicted in Figure 1 this system consists of different models. Flight movements are simulated using the Trajectory Calculation Module (TCM, Linke, 2008; Lührs, 2013), which computes aircraft trajectories from lift-off to touch-down applying a kinetic mass-point model that provides simplified equations of motion known as Total Energy Model. One of the key features implemented in the TCM for the purpose of this research is the use of the advanced aircraft performance model (APM) BADA (Base of Aircraft Data) version 4, which allows for modeling typical flight operations realistically. The BADA 4 models cover the whole flight

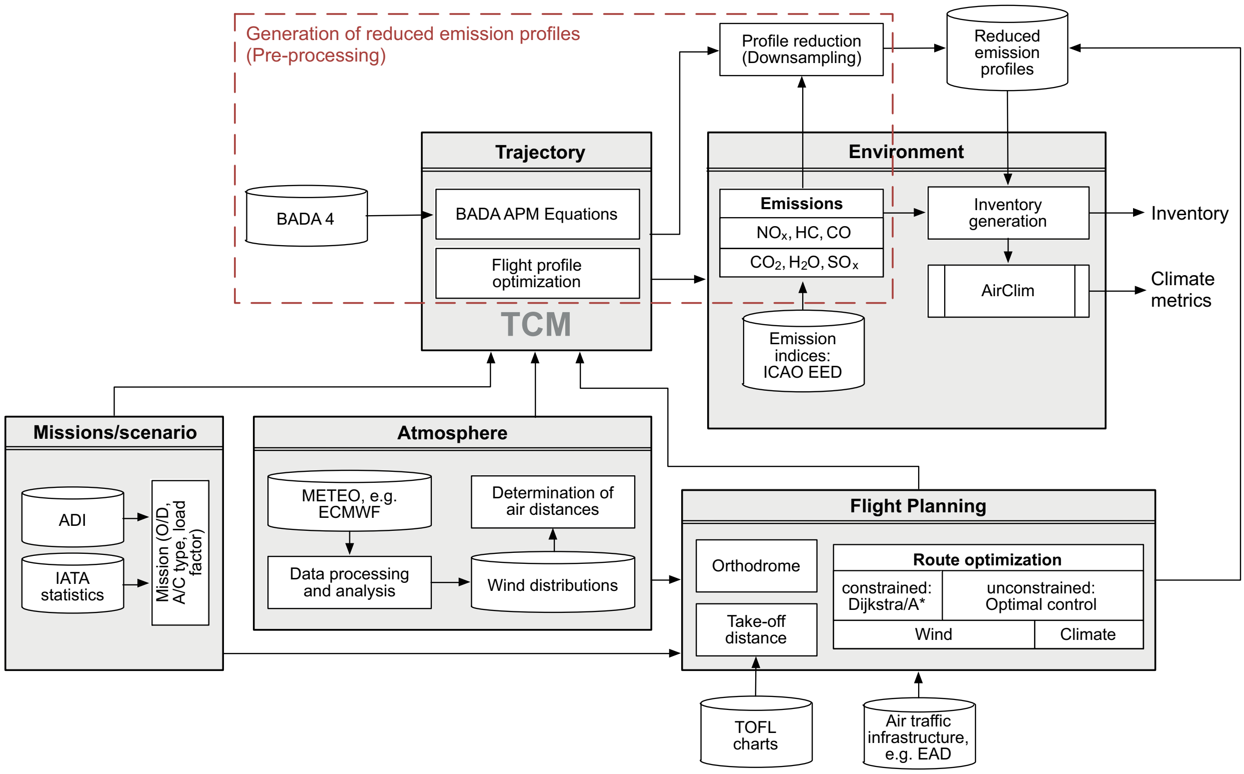

Figure 1: Schematic diagram of the developed modeling system (abbreviations: A/C – aircraft; O/D – origin/destination; see text for further acronyms).

envelope, capture the flight physics more accurately than previous model versions and thus can be used to determine e.g. optimized vertical profiles, i.e. optimum altitudes and speeds (Mouillet, 2013). Using this capability airline-preferred cruise profiles can be estimated including the location of step climbs depending on the selected step climb strategy and the heading-dependent available flight levels. Regarding meteorological data the TCM can either be used with International Standard Atmosphere conditions or with real atmospheric data in NetCDF or GRIB format that can e.g. be obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF).

The consideration of wind in system-wide analyses of new operational concepts is one of the main contributions of the work with respect to the methodology. From an aircraft performance point of view wind affects the mission and thus flight time, fuel burn and emissions by changing the actual distance the aircraft has to cover, also known as (still) *air distance*. Whereas tailwind shortens the air distance of a flight for a given ground distance, headwind and crosswind increase it. As the aircraft flies, its (true) airspeed overlays with the wind speed in a vector form; in a crosswind situation some of the aircraft's energy is needed to compensate for the drift by applying a wind correction angle in order to maintain a desired course.

For considering the described wind effect a new and highly efficient method has been developed which is able to process daily wind data and statistically analyse it resulting in a data set of local wind distributions. This database contains discrete wind cases (combinations of wind speed and direction) and their respective frequency of occurrence for every point in the grid. This data is used to determine characteristic mean still air distances for any given flight route as a basis for system-wide analyses valid for longer periods of time, e.g. one year (Swaid, 2013; Linke, 2016). These air distances are eventually used in the emission distribution calculation explained below to account for wind.

Moreover, a flight planning functionality is included that provides route optimization capabilities with respect to different criteria. This is useful whenever realistic airline operations should be modeled. Today, many aircraft operators already follow so-called wind-optimal routes that minimize flight time and fuel consumption for a given mission in the presence of wind. Such wind-optimal routes can be determined either without any constraints using an optimal control approach (Lührs, 2013) or applying a constraining air traffic services (ATS) route network solving a shortest-path problem (combined Dijkstra/A* method, Swaid, 2014). For this purpose the model accesses the European Aeronautical Information Services Database (EAD), a comprehensive air traffic infrastructure database containing geographical data on airports, waypoints and complete ATS routes. The required take-off field length (TOFL) at a given airport for predominant temperature and pressure conditions can be determined with a TOFL model that is made up by charts taken from airport compatibility manuals.

For the environmental analysis the modeling system includes an emission model that determines the gaseous emissions along resulting trajectories from TCM. Here, both emission species that are produced proportionally to fuel burn, i.e. CO_2, H_2O, as well as species that develop in a non-proportional way, i.e. NO_x, HC and CO, are determined. For the latter the state-of-the-art fuel flow correlation method Boeing Fuel Flow Method 2 (DuBois and Paynter, 2006) is applied in combination with Emission Indices for sea level conditions obtained from the Engine Emission Databank (EED) by the International Civil Aviation Organization (ICAO). Afterwards, these emission distributions can be mapped into a geographical grid, which allows for the generation of emission inventories by superposing the emissions of a large number of flights. These inventories are then used by the climate-chemistry response model AirClim (Grewe and Stenke, 2008; Dahlmann et al., 2016) to determine the climate impact resulting from the emissions. The basis of this method constitute atmospheric concentration changes of radiative forcing agents as a function of latitude and altitude caused by unit emissions, which were pre-calculated using the complex climate-chemistry model ECHAM4.L39(DLR)/CHEM (Hein et al., 2001) as well as the corresponding radiative forcing (RF). The model has been evaluated with respect to concentration changes of water vapour and ozone, and especially RF values for changes in the flight altitude by comparing AirClim results with results from detailed atmosphere-chemistry models (Grewe and Stenke, 2008; Grewe and Dahlmann, 2012; Dahlmann et al., 2016). In addition, a comparison of the vertical sensitivity of aircraft emissions on the RF between AirClim, LEEA (Köhler et al., 2008; Rädel and Shine, 2008) and E39CA has been performed in Grewe and Dahlmann (2012). The results clearly show a good representation of the RF response caused by altitude changes agreeing within a range of ±10 % for ozone, contrails and ±15 % for water vapour. The model has been previously applied to assess the climate impact of aircraft designs and trajectory options in a variety of studies (Grewe et al., 2010; Koch et al., 2012; Grewe et al., 2016; Dahlmann et al., 2016).

In order to reduce the necessary number of trajectory simulations in the course of a global analysis with a large number of flights the developed modeling system makes use of a method that is commonly applied to reduce the complexity during the generation of emission inventories. So-called *reduced* emission profiles are used that were derived from pre-calculated trajectories and emission distributions. For each considered aircraft type (19 wide-body aircraft types were used that cover the entire Airbus and Boeing wide-body aircraft fleet), missions of different air distances and load factors have been simulated with TCM and the corresponding emission distributions along these trajectories were determined. For all missions it was assumed that the pilot flies as close as possible to the optimum altitude and selects the so-called Long-Range Cruise mach number as appropriate cruise speed. This mach number generally represents a good compromise between fuel consumption and flight time. The resulting standardized profiles are then down-sampled and only the relevant aircraft state parameters (flown air distance, flight time, altitude, fuel flow, emission flows of all species) at the profile vertices are stored into a database. Assuming a linear parameter gradient between each two flight phase vertices, from those few points an entire profile can be recreated. An analysis of the errors of all profiles in the database resulting from this linearization has revealed that it is generally in the order of ±0.1 percent and thus can be neglected. With given mean air distances determined by the approach described above to consider the wind effect, for each flight the appropriate profile is obtained from the database. Finally, the emission profile is mapped into the geographical grid by scaling it according to the segment-wise air distance values to the respective ground distance and aligning it to the flight path. Thereby, this method accounts for the effect of wind and can also be used to consider potential horizontal flight inefficiencies. Through the above mentioned combination of trajectory computation, flight planning and environmental analysis capabilities, the modeling system can be used to evaluate the environmental effects resulting from changes of flight and fleet operations (Linke, 2016).

3 Study set-up

In this study we apply the modeling system to analyse the implications Intermediate Stop Operations have on global aviation emissions and climate. For this purpose, we generate emission inventories for two scenarios and compare them to each other: the reference case is made up of a large set of flight missions (approximately 1.023 million annual flights) in which every mission is conventionally performed as direct flight, whereas the ISO case contains for each mission two flight segments connecting the origin to the destination airport via a stopover at the refueling airport. As the short-term effects of ISO are of interest in this study, it is assumed that each ISO mission is performed by the same aircraft type as used for the direct flight (*self-substitution*) and no further changes of the aircraft fleet need to be considered. Flight movement data is obtained from Sabre ADI (Airport Data Intelligence, now: Sabre AirVision Market Intelligence) flight schedule database (http://www.airdi.net) for the first quarter of 2010 and flight frequencies are scaled up to the period of one year. As previous studies have revealed that only wide-body aircraft actually show a fuel saving potential in self-substitution on mission lengths above 2500 NM (Linke et al., 2012), this study is limited to the global wide-body aircraft fleet. In order to estimate aircraft masses region-dependent passenger load factors are calculated based on economics statistics published regularly by the International Air Transport Association (http://www.iata.org/economics).

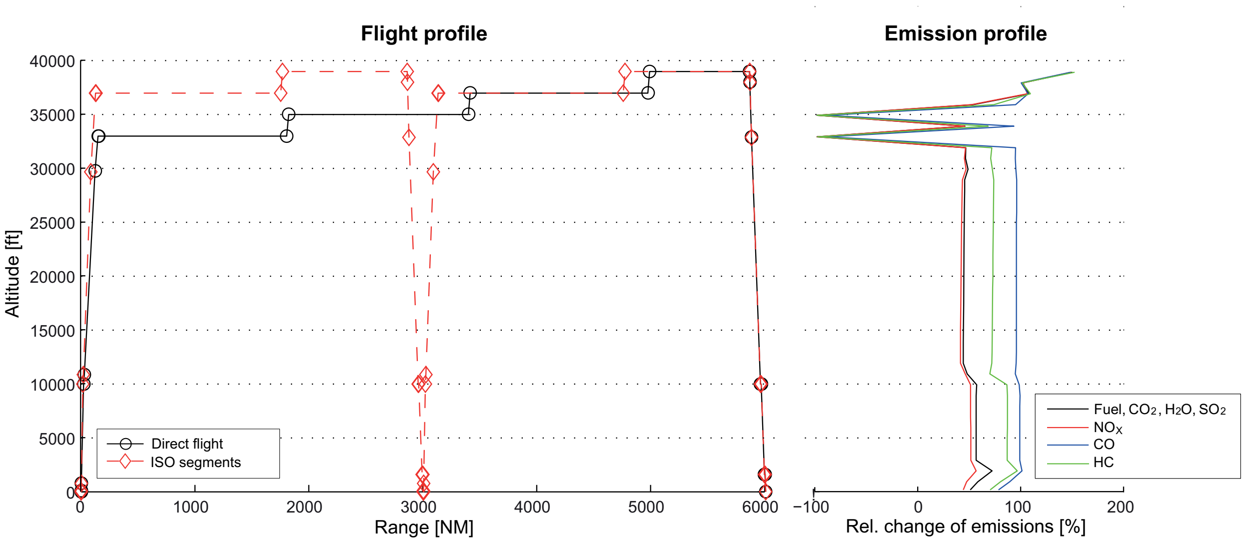

Figure 2: Change of flight altitudes and vertical emission distribution due to ISO shown on an exemplary 6000 NM mission flown with an Airbus A340-600 aircraft assuming an ideal intermediate landing (in the middle).

In preparation for the inventory calculation, the stopover locations have to be defined; using an exhaustive search algorithm for each ISO mission the respective airport is determined by optimization, assuming that location is selected for the stopover which leads to the maximum fuel savings for the specific mission. The airports' geographical coordinates are obtained from the EAD database which is filtered for only major airports with at least one asphalt-surfaced runway and an instrument landing system assuming that certain equipment needs to be installed such that commercial wide-body airplanes are able to perform an intermediate stop there. Moreover, a minimum runway length needs to be available which is defined by the required TOFL of the aircraft for the given take-off weight (TOW) and the ambient conditions at the field. The meteorological data is taken from ECMWF for a grid of $0.75° \times 0.75°$ for the period of one year (2012). The statistical wind distributions mentioned above are used to account for the effect of wind by considering annual mean air distances between every airport pair. These air distances are used to obtain the respective reduced emission profiles from the database. By projecting these emissions into the ground-based grid additional emissions caused by headwind are attributed to the grid cells; on the contrary, in case of tailwind by stretching the profiles to match the ground distances, a reduced amount of emissions is assigned to the grid cells. For the sake of simplicity only orthodromic (great circle) routes are assumed.

4 Results

The introduction of ISO affects the amount and the distribution of engine exhaust emissions and thus leads to a change of the climate impact. In the following the results of the study are presented. After a principal investigation of the emission distribution changes on a generic mission the results of a system-wide analysis on a global level considering real flight networks, airport locations and meteorology are given.

4.1 Generic mission profile

Figure 2 shows the vertical flight profile of a standard 6000 NM mission simulated with an Airbus A340-600 aircraft. A distinct stepped climb cruise from an initial cruise flight level of 33000 ft (FL 330) up to FL 390 can be observed. As the aircraft weight decreases over time due to the continuous fuel burn the optimum altitude of the aircraft increases (Airbus Customer Services, 2002). The optimum altitude is defined as the altitude at which the aircraft's specific range becomes maximum. In today's flight operations step climbs are conducted to follow the optimum altitude as good as possible while ensuring compliance with air traffic management (ATM) constraints. Besides the profile of the direct flight mission, also the profiles of the two resulting flight segments for a flight performing a stopover at the ideal location after 3000 NM are shown. It can be seen that especially the first segment has a higher initial cruise flight level than the direct flight. The reason for this is the reduced TOW in the ISO case corresponding to a higher optimum altitude. Assuming that pilots try to fly as close as possible to the optimum altitude for fuel economy reasons, this fact would lead to a shift of cruise emissions by approximately 4000 ft upwards (in this example).

The relative changes of the amounts of the different emission species per altitude layer are also depicted in the emission profile in Figure 2. In addition, Table 1 shows the emission split between cruise and climb/descent both for the relative emission amounts and for the emission changes caused by ISO. It can be seen that below cruise there is an increase of CO emissions by about 96 % and an increase of HC emissions by approximately 83 % due to ISO. This can be attributed

Table 1: Relative amounts of emissions and emission changes below (< FL 310) and at (≥ FL 310) cruise altitude.

Species	Direct flight		Changes due to ISO		
	≥ FL 310	< FL 310	$\sum$	≥ FL 310	< FL 310
Fuel, CO_2, H_2O, SO_2	93.50 %	6.50 %	−8.94 %	−13.33 %	+54.11 %
NO_x	89.29 %	10.71 %	−12.28 %	−19.65 %	+49.19 %
CO	60.35 %	39.65 %	+42.27 %	+6.76 %	+96.30 %
HC	92.02 %	7.98 %	+6.81 %	+0.25 %	+82.55 %

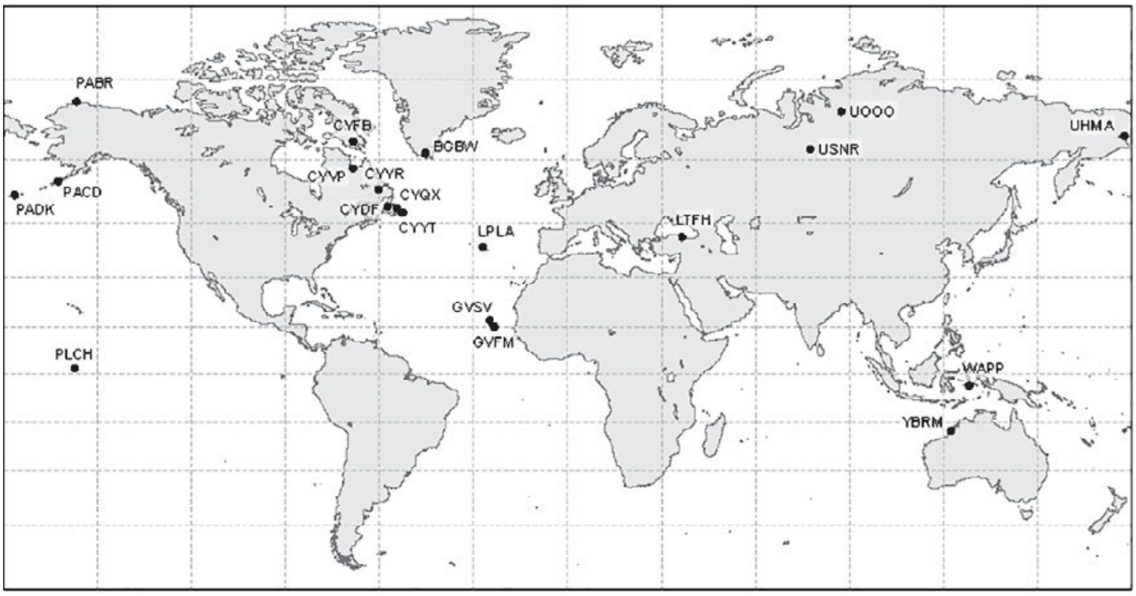

Figure 3: Geographical distribution of the top 20 most frequented ISO airports in the world.

to the doubling of flight phases with low thrust settings (e.g. descents and landings) in which the mixing process in the combustor is rather inefficient. Products developing proportionally to fuel burn, i.e. CO_2, H_2O and SO_2, as well as NO_x increase by 49–54 % during climb in the ISO case, because the lower TOW allows for a steeper climb and less time is spent in grid cells below cruise flight level. The increased cruise altitudes on the first mission segment cause a reduction of emissions by nearly 100 % on lower cruise flight levels (FL330 and FL350 in this example), whereas an emission increase is caused on the upper flight levels (FL370 and FL390), as can be seen in Figure 2. There is also a relative emission increase on the intermediate flight levels FL340 and FL360 (for ATM reasons there has to be a minimum separation between the available flight levels), which the aircraft only briefly flies through, due to the doubling of climb and descent segments; however, the absolute amount of emissions on these levels is very small. This example helps understanding the general phenomena connected to profile adjustments due to ISO. In reality, suitable airports for intermediate stops are not ideally located and mission lengths differ considerably. Therefore, a system-wide study is needed to quantify the effects that can be expected in a real operational environment.

4.2 System-wide analysis

In a first step for each mission the optimum stopover airport was determined. For 86.8 % of all simulated long-haul flights appropriate airports were found that lead to positive fuel savings compared to the direct flight. It is assumed that as soon as positive savings can be achieved by a stopover the flight is operated in ISO mode. The remaining flights are conducted in direct mode. Table 2 shows the 20 most affected airports together with the number of additional landings and take-offs due to ISO. It is not surprising that these airports are mainly located in regions which are crossed by long-haul flights, including Newfoundland, Greenland, Siberia as well as some islands in the Atlantic and Pacific Oceans. A map of these airports is depicted in Figure 3. Overall 440 individual airports were identified that serve as stopover locations for ISO missions. Approximately 40 % of all intermediate stops can be accommodated by the 20 most frequented airports in Table 2. These findings are consistent with results from previous studies, including Linke et al. (2011) and Langhans et al. (2013), however, here we consider the effect of wind for the first time. It should be noticed, that in reality, most of the listed airports would not have the required capacity to accommodate the additional landings and take-offs right now. How-

Table 2: Top 20 most frequented ISO airports with number of additional landings and take-offs.

Rank	ICAO	Airport name	Location	Flights	
1	CYQX	Gander International Airport	Gander, Newfoundland, Canada	56090	6.31 %
2	CYYT	St. John's International Airport	St. John's, Newfoundland, Canada	46387	5.22 %
3	LPLA	Lajes Airport	Lajes, Azores, Portugal	27680	3.12 %
4	CYYR	Goose Bay Airport	Goose Bay, Labrador, Canada	26432	2.97 %
5	BGBW	Narsarsuaq Airport	Narsarsuaq, Greenland	23685	2.67 %
6	PADK	Adak Island Airport	Adak (Island), Alaska, USA	19239	2.17 %
7	YBRM	Broome International Airport	Broome, Western Australia, Australia	14586	1.64 %
8	CYFB	Iqaluit Airport	Iqaluit, Nunavut, Canada	12401	1.40 %
9	GVSV	Cesária Évora Airport	São Vicente, Capeverde	11878	1.34 %
10	CYVP	Kuujjuaq Airport	Kuujjuaq, Québec, Canada	11856	1.33 %
11	LTFH	Carsamba Airport	Samsun, Turkey	11644	1.31 %
12	PLCH	Cassidy International Airport	Banana, Kiritimati (Island), Kiribati	10959	1.23 %
13	WAPP	Pattimura Airport	Ambon, Indonesia	10946	1.23 %
14	GVFM	Nelson Mandela International Airport	Praia, Santiago (Island), Capeverde	10923	1.23 %
15	USNR	Raduzhny Airport	Raduzhny, Russia	9950	1.12 %
16	CYDF	Deer Lake Airport	Deer Lake, Newfoundland, Canada	9604	1.08 %
17	PABR	Wiley Post-Will Rogers Memorial Airport	Barrow, Alaska, USA	8874	1.00 %
18	PACD	Cold Bay Airport	Cold Bay, Alaska, USA	8797	0.99 %
19	UHMA	Ugolny Airport	Anadyr, Russia	8658	0.97 %
20	UOOO	Norilsk Alykel Airport	Norilsk, Russia	7495	0.84 %
				348086	39.17 %

ever, it is assumed that as soon as the introduction of the ISO concepts starts, a demand is created gradually at these airports that would lead to the necessary infrastructural expansions.

Based on the identified ISO airports, emission inventories were calculated both for the direct flight scenario and for the ISO mode scenario. The difference of these inventories with regard to pure fuel consumption is shown in Figure 4. Positive peaks (large differences to reference case) are marked in red. They can be found in those regions that were identified before, as additional emissions are produced near airports accommodating intermediate stops. From the latitude and altitude profiles a shift of emissions towards higher latitudes and altitudes can be observed. The latter effect had already been discussed on a generic level in the previous section.

Overall, the introduction of Intermediate Stop Operations could save approximately 3 million tons of fuel per year representing 4.8 % of the entire fuel consumption in the reference scenario, i.e. the respective wide-body flights. Given an approximate portion of the selected flights of 28 % from the global fuel consumption (scheduled air traffic), these savings amount to 1.3 % globally. Realizing ISO on a global scale would only require 0.4 % extension of the flown ground distance. In general this implies that suitably located airports can be found without requiring large detours. ISO can even achieve a reduction of the flown air distance by 0.15 %, as in many cases airports can be found that are located along the wind-optimal route shortening on average the actual flight distance in the presence of winds. Figure 5 shows the emission inventories also for NO_x and CO species. While CO_2, H_2O and SO_2 are reduced by 4.8 % with respect to the direct flight scenario, there is a 4.6 % reduction in NO_x, an increase by 33.3 % of CO and an increase of HC by 43.4 %. The latter findings indicate a potential LAQ issue, especially at highly frequented ISO airports, and should be subject to further investigation. Figure 6 depicts the H_2O inventory projections into the longitude-altitude plane both for the direct flight and the ISO scenario. Obviously most cruise emissions are moved to approximately 12 km altitude due to the shift of initial cruise flight levels to higher altitudes by 4000–6000 ft. Additionally, the number of step climbs in ISO mode is reduced due to shorter segment lengths and therefore the altitude band is narrowed from 7000 ft to approximately 3000 ft.

Finally, a climate impact assessment is performed. We are evaluating the long-term future climate change of aviation when introducing ISO and compare this scenario to a reference case without ISO. Hence, we are evaluating the changes in the long-term climate impact for the mitigation strategy "Flying ISO". A suitable climate metric is the Average Temperature Response on a 100 year time horizon (e.g. Grewe and Dahlmann, 2015; Koch, 2013). The ATR is calculated as the time integral of the temporal course of the near-surface temperature change divided by the time horizon and thus, as opposed to other metrics like RF or Global Warming Potential, allows for the quantification of a resulting temperature change that takes into account the dynamics of the earth-climate system. As base scenario the Fa1 growth scenario defined by the ICAO Forecasting and Economic Analysis Support Group was selected, which includes assumptions regarding the temporal development of global emissions. This emission scenario is hence based on conventional techniques and represents a business-as-usual-sccenario. The emission

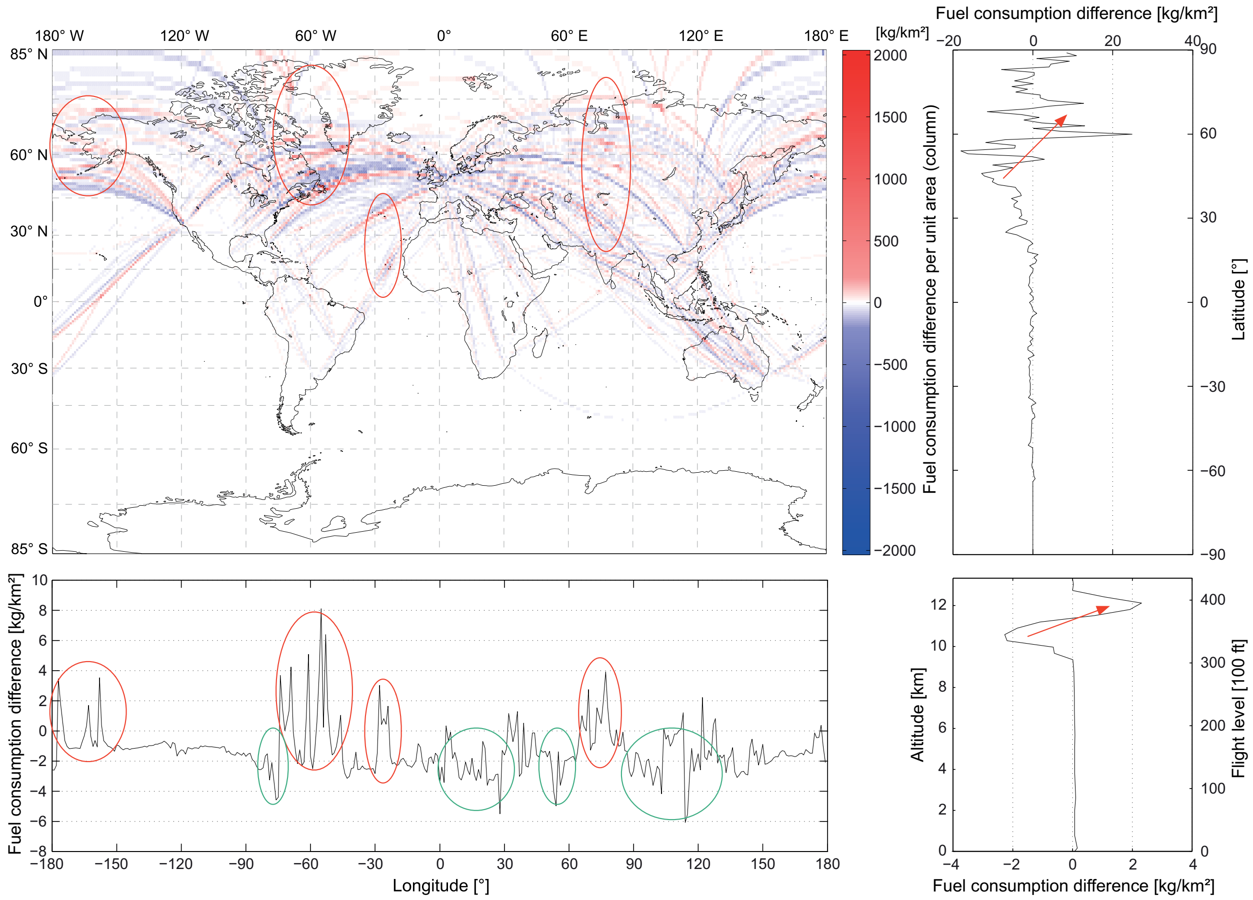

Figure 4: Redistribution of global fuel consumption due to ISO on long-haul missions (differences from direct flight scenario) in the first quarter of 2010; top left: geographical distribution of changes in the fuel sums per grid column; top right: latitude profile (zonal); bottom left: longitude profile (meridional); bottom right: altitude profile.

effects caused by the ISO concept were scaled by the evolution factors from the scenario to simulate traffic growth as well as technological advances and the ramp-up of the ISO concept introduction was assumed to last 10 years starting in 2015. The results can be seen in Figure 7. Although the absolute amount of emissions of the species CO_2, H_2O, SO_2 and NO_x can be reduced through ISO the Average Temperature Response increases by 2.3 %, which is one of the major findings of the study. This temperature increase of 2.3 % results from reduced warming effects of CO_2 (−0.72 %) and contrails (−0.35 %), which are over-compensated by an increase in warming from NO_x emissions (+2.12 %) and H_2O emissions (+1.26 %).

The most important effect is the increase in cruise altitude at mid latitudes for ISO compared to the reference situation. This results in a shift of emissions to slightly higher altitudes, where mixing processes are slower and hence result in a larger accumulation of nitrogen oxides and water vapor. The relative change in climate impact is largest for water vapor (almost 25 %, Fig. 7). The radiative forcing of water vapor generally increases with the altitude at which it is released (Grewe and Stenke, 2008; Lee et al., 2010). The upwards shift of flight levels into the lower stratosphere therefore intensifies the greenhouse effect of H_2O. This effect is even increased by a slight shift of emissions to higher latitudes as the tropopause altitude falls towards the poles. The increase of cruise altitude also leads to an increase in ozone and to an increase in methane lifetime, which both are contributing to an increased warming. These results are consistent with previous findings, e.g. Frömming et al. (2012); Søvde et al. (2014); Dahlmann et al. (2016).

On the other hand contrail formation is avoided, since many flights are above the main contrail formation area. The radiative forcing by contrails reaches its maximum just below the tropopause and is dependent on contrail coverage and optical properties. Above the (climatological) tropopause the radiative forcing by contrails then rapidly decreases with increasing altitude (Lee et al., 2009). The shift to higher altitudes and latitudes therefore helps avoiding contrails and reduces the warming from contrails. The results are largely in agreement with Frömming et al. (2012). In combination, these findings show that in contrast to speculations from previous studies a systematic introduction of ISO on a global level would not necessarily have positive implications for the climate, at least not for the current aircraft fleet. Our results show that the increase in warming effects from NO_x and H_2O emissions cannot be compensated by a reduction in the warming from less CO_2 emissions and from less contrails.

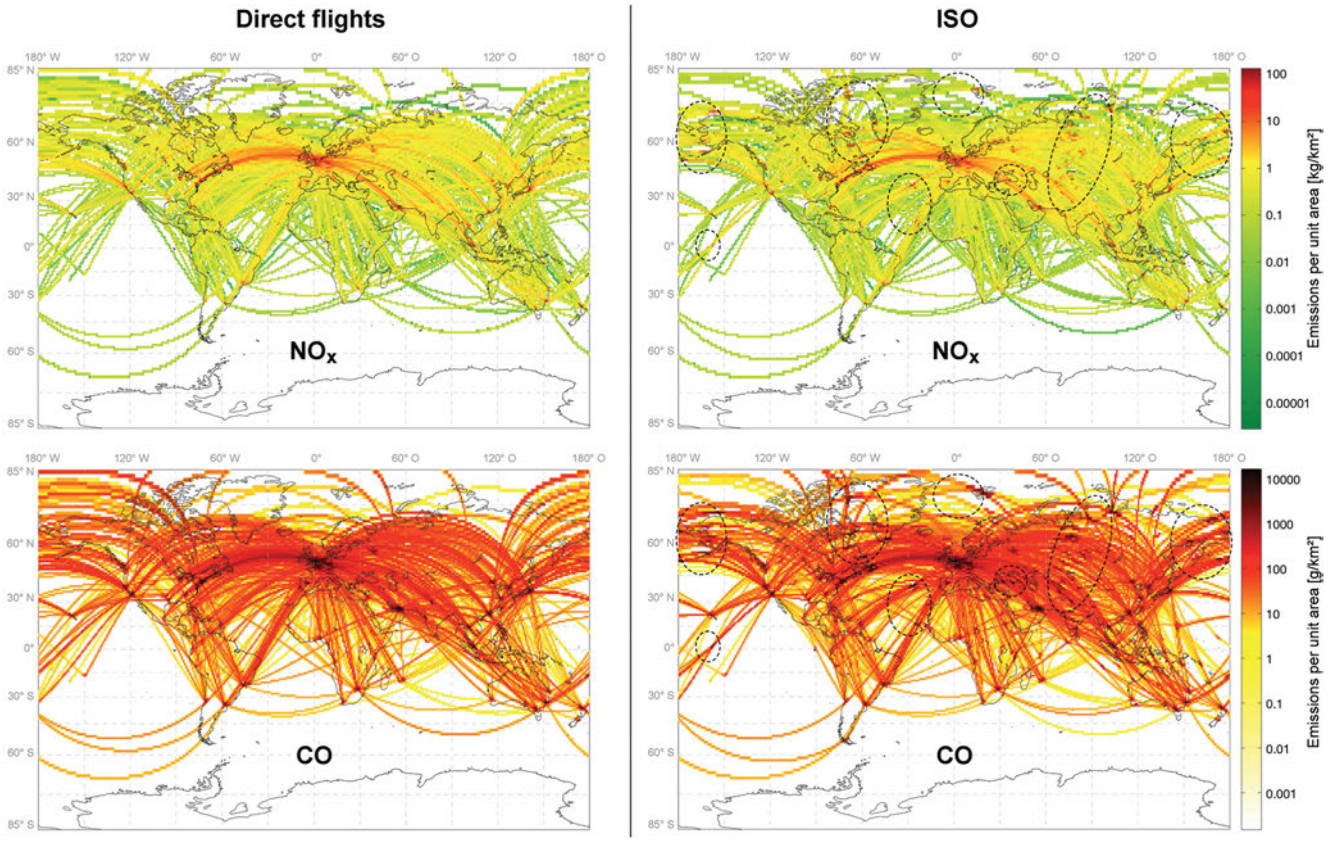

Figure 5: Aggregated geographical emission distribution for the first quarter 2010; left: direct flights, right: ISO mode.

5 Discussion

We have investigated the climate impact of an immediate introduction of intermediate stop operations. Naturally, the results depend on assumptions we made. This includes the choice of the climate metric, regarded atmospheric processes, impacts from ground emissions or possibilities of re-designing the aircraft, which we discuss here in more detail.

In general, the choice of the climate metric plays a crucial role in any assessment of aviation technologies (Fuglestvedt et al., 2010). However here, we ask the question "What would be the long-term impact to the climate if we started introducing ISO now?". And this limits the choice of climate metrics suitable to answer this question (Grewe and Dahlmann, 2015) and the impact of the choice of a suitable climate metric on the results is low (Grewe et al., 2014). The time horizon would have played a very crucial role, if we had chosen a pulse emission, however then we would have asked a different question. For an increasing emission scenario, as taken here into account, short-term and long-term climate effects are more balanced (Grewe and Stenke, 2008, their appendix).

The results presented above strongly depend on the balance of the contributions from the various radiative forcing agents to the overall climate response. Many of the effects are estimated with large uncertainty ranges (Lee et al., 2009). However, Dahlmann et al. (2016) showed that these uncertainties are not limiting the assessment of technology options, which include variations in cruise altitude. Additionally, some potential impacts, such as the effect of aerosol emissions on clouds were not taken into account here, since the scientific understanding of these potential impacts is not mature enough to be included here.

Further uncertainties result from inaccuracies in the emission quantification which are caused by model effects in the trajectory calculation and the fuel flow correlation method. Comparisons between BADA 4 and highly detailed aircraft performance data from Airbus have shown, that for the respective aircraft types the fuel flow modelling error is 2.3 % on average (Nuic, 2013). Furthermore, for a fuel flow that is precisely known Schulte et al. (1997) found by comparison to in-situ measurements that the Boeing Fuel Flow Method 2 tends to systematically underestimate real NO_x emissions by approximately 11 %. Other aspects that influence the predicted fuel flow are the aircraft mass as well as the assumed altitude and speed profile. Here, we generally simulate optimum profiles such that the reduced drag might slightly underestimate the fuel flow as well. However, in combination the emission quantification errors still seem to be acceptable, especially given the fact,

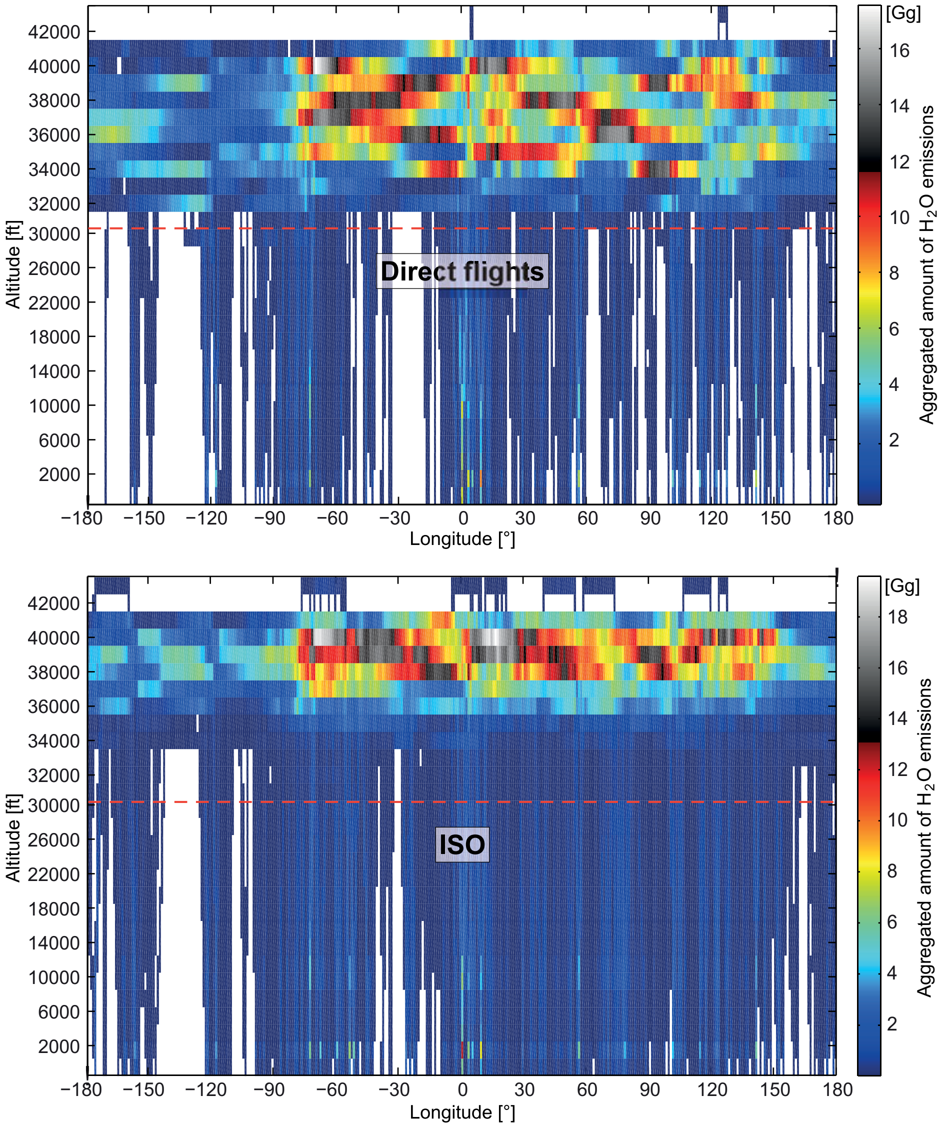

Figure 6: Distributions of H_2O emissions (absolute values meridionally aggregated) in longitude-altitude plane for the direct flight mode (top) and the ISO mode (bottom); red line depicts a break in the vertical scale.

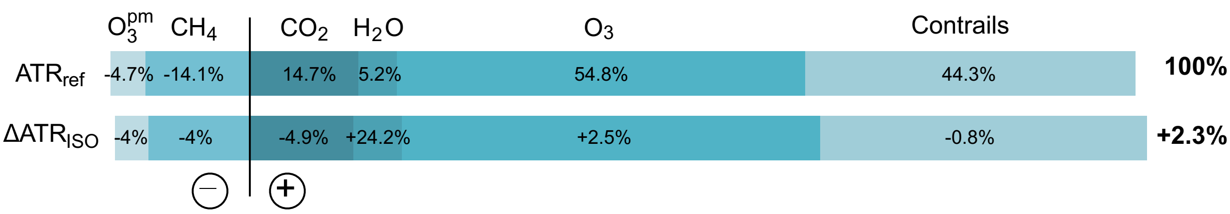

Figure 7: Climate impact changes (metrics: ATR^{100}) due to ISO separated by contributions of different radiative forcing agents (reference case: percentage of overall ATR; ISO case: relative changes with respect to reference case).

that for the analysis the focus is laid on a relative comparison rather than providing absolute numbers.

Emissions from aircraft ground operations were not taken into account. However, as this study focuses on the global emission distribution and the climate impact resulting primarily from emissions in the upper troposphere and lower stratosphere this simplification is considered to be appropriate. Moreover, on long-haul flights as considered in this work the percentage of time, fuel and emissions spent during flight by far dominates the ground operations portion. For a more detailed study on the implications of the ISO concept on local air quality aspects at the affected airports, emissions from ground operations need to be considered.

Furthermore, it should be noticed that the results refer to a scenario in which a short-term introduction of

ISO without any adaptations to the existing aircraft fleet and self-substitution are assumed. Given the current low kerosene price one can argue that this scenario is at present rather unrealistic. As mentioned in the introduction there have been studies also on the cost implications of the ISO concept revealing that in spite of the possible fuel savings there are only few long-haul routes on which airlines actually are able to reduce the Direct Operating Costs on their flights (Linke et al., 2012). The reason for this is that fuel costs are only one portion (up to 50 % on long-haul flights) of the overall DOC bill and ISO induces additional costs that offset the fuel cost savings. These additional costs are partly caused by the increased flight times (e.g. higher crew costs and reduced aircraft utilization) and include additional landing and en-route navigation fees as well as increased maintenance costs for engine and airframe due to the doubling of flight cycles. Furthermore, in a society for which comfort is of high significance and an omnipresent part of the life-style the passengers' willingness to accept longer flight times and intermediate stops is limited unless flight tickets are significantly cheaper than for direct flights. This would further reduce the profit margin of the operator. In combination with optimistic assumptions regarding the available capacity at the ISO airports, a global short-term implementation of the ISO concept is therefore rather unlikely. The results should be understood as indications of maximum possible savings and the corresponding climate impact in a "what-if" manner.

A more realistic scenario may consider ISO with aircraft types that are redesigned and optimized for shorter ranges. According to e.g. Langhans et al. (2013), in this case higher cost savings can be expected that would make an adoption for airlines easier. Such an aircraft would have a smaller wing and a lower initial cruise altitude than the original long-haul aircraft fuelled for only one ISO leg. It is therefore expected, that the utilization of redesigned medium-range aircraft would rather shift cruise emissions to lower altitudes which consequently could turn the negative climate impact of water vapour and nitrogen oxides into a positive one while saving even more fuel.

Based on these findings, there is the need for a further system-level study taking into account redesigned medium-range aircraft. Such a study should include a realistic DOC model and analyse various design options with different range and cruise altitude requirements. For the existing aircraft fleet it could be investigated to what extent decreasing cruise altitudes during ISO mode would reduce the negative effects of the concept. As this also reduces the potential fuel savings of the concept a trade-off needs to be done and an optimization could be conducted to determine the optimum altitude for the ISO missions in order to have a combined environmental and fuel saving benefit. However, we expect a climate impact reduction for ISO even with existing aircraft, avoiding the higher flight altitude in the first flight segment and hence reducing the fuel savings.

6 Conclusions

A method has been presented that allows for the assessment of new operational concepts with respect to their impact on global emissions and climate. The modeling system comprises a trajectory simulation module, flight planning functionalities, atmospheric models including an efficient wind distribution method as well as models for generating global emission inventories and calculating their climate impact. The trajectory calculation makes use of the most advanced aircraft performance models, namely BADA 4, provided by EUROCONTROL, and for the first time provides means to model flight operations including cruise profiles from an airline point-of-view more realistically. A mechanism for complexity reduction was applied by using a database of precalculated reduced emission profiles. The method was applied to analyse the environmental implications of the ISO concept for today's worldwide aircraft fleet. A large air traffic scenario containing all world-wide long-haul flights in 2010 was considered and the effect of wind was accounted for.

Overall, 4.8 % of fuel can be saved through ISO globally, assuming a full coverage of the operational concept. Airports serving as suitable stopover airports are located mainly in Newfoundland, Greenland, Siberia, Azores and Capeverdes. While most emission species can be reduced by ISO, there would be an increase of 33–43 % of HC and CO emissions due to the doubling of descent and landing phases causing a potential LAQ issue. Due to a lower TOW on ISO missions, the initial cruise flight levels are shifted up and the altitude band is narrowed as flight segments are shorter and less step climbs are required. This emission relocation causes a warming climate impact compared to the direct operations by 2.3 % in the Average Temperature Response over 100 years as the increased warming effects, caused by the emitted NO_x and H_2O, dominates over the reduced warming effects from CO_2 and contrails.

As discussed above, a more realistic adoption of medium-range aircraft for flying ISO could on the other hand have a positive climate impact due to the expected lower cruise altitudes. A more detailed analysis and verification of this should be subject of future research.

Acknowledgments

Parts of this work were carried out within the DLR internal project *WeCare*. The authors would like to thank the project team for fruitful discussions leading to the presented results. Furthermore, the authors appreciate the contributions by some colleagues at DLR, particularly Majed Swaid and Benjamin Lührs who were involved in the development of the modeling system and contributed with their valuable knowledge on trajectory calculation and wind modeling.

References

Airbus, 2014: Flying on demand - global market forecast 2014–2033. – Technical report, AIRBUS S.A.S., 31707 Blagnac Cedex, France.

Airbus Customer Services, 2002: Getting to grips with aircraft performance. – Technical report, Flight Operations Support & Line Assistance.

Brasseur, G.P., M. Gupta, B.E. Anderson, S. Balasubramanian, S. Barrett, D. Duda, G. Fleming, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.N. Halthore, S.D. Jacob, M.Z. Jacobson, A. Khodayari, K.-N. Liou, M.T. Lund, R.C. Miake-Lye, P. Minnis, S. Olsen, J.E. Penner, R. Prinn, U. Schumann, H.B. Selkirk, A. Sokolov, N. Unger, P. Wolfe, H.-W. Wong, D.W. Wuebbles, B. Yi, P. Yang, C. Zhou, 2016: Impact of aviation on climate: FAA's aviation climate change research initiative (ACCRI) phase ii. – Bull. Amer. Meteor. Soc. **97**, 561–583, DOI: 10.1175/BAMS-D-13-00089.1.

Creemers, W., R. Slingerland, 2007: Impact of intermediate stops on long-range jet-transport design. – In: 7th AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Belfast, Northern Ireland, American Institute of Aeronautics and Astronautics.

Dahlmann, K., V. Grewe, C. Frömming, U. Burkhardt, 2016: Can we reliably assess climate mitigation options for air traffic scenarios despite large uncertainties in atmospheric processes? – Transportation Research Part D: Transport and Environment **46**, 40–55, DOI:10.1016/j.trd.2016.03.006.

DuBois, D., G.C. Paynter, 2006: "fuel flow method2" for estimating aircraft emissions. – In: SAE Technical Paper 2006-01-1987. SAE International.

Frömming, C., M. Ponater, K. Dahlmann, V. Grewe, D.S. Lee, R. Sausen, 2012: Aviation-induced radiative forcing and surface temperature change in dependency of the emission altitude. – J. Geophys. Res. Atmos. **117**, published online, DOI:10.1029/2012JD018204 D19104.

Fuglestvedt, J., K. Shine, T. Berntsen, J. Cook, D. Lee, A. Stenke, R. Skeie, G. Velders, I. Waitz, 2010: Transport impacts on atmosphere and climate: Metrics. – Atmos. Env. **44**, 4648–4677, DOI:10.1016/j.atmosenv.2009.04.044

Gauss, M., I.S.A. Isaksen, D.S. Lee, O.A. Søvde, 2006: Impact of aircraft NO_x emissions on the atmosphere – tradeoffs to reduce the impact. – Atmos. Chem. Phys. **6**, 1529–1548, DOI: 10.5194/acp-6-1529-2006.

Green, J.E., 2005: Air travel – greener by design: Mitigating the environmental impact of aviation: Opportunities and priorities. – Technical report, Report of the Science and Technology Sub-Group.

Grewe, V., K. Dahlmann, 2012: Evaluating Climate-Chemistry Response and Mitigation Options with AirClim. – Springer Berlin Heidelberg, Berlin, Heidelberg, 591–606.

Grewe, V., K. Dahlmann, 2015: How ambiguous are climate metrics? and are we prepared to assess and compare the climate impact of new air traffic technologies?. – Atmos. Env. **106**, 373–374, DOI:10.1016/j.atmosenv.2015.02.039.

Grewe, V., A. Stenke, 2008: Airclim: an efficient tool for climate evaluation of aircraft technology. – Atmos. Chem. Phys. **8**, 4621–4639, DOI:10.5194/acp-8-4621-2008.

Grewe, V., M. Dameris, C. Fichter, D.S. Lee, 2002: Impact of aircraft NO_x emissions. part 2: Effects of lowering the flight altitude. – Meteorol. Z. **11**, 197–205, DOI: 10.1127/0941-2948/2002/0011-0197.

Grewe, V., M. Plohr, G. Cerino, M.D. Muzio, Y. Deremaux, M. Galerneau, de P. Saint Martin, T. Chaika, A. Hasselrot, U. Tengzelius, V.D. Korovkin, 2010: Estimates of the climate impact of future small-scale supersonic transport aircraft results from the HISAC EU-project. – Aeronautical J. **114**(1153), 199–206, DOI:10.1017/S000192400000364X.

Grewe, V., T. Champougny, S. Matthes, C. Frömming, S. Brinkop, O.A. Søvde, E.A. Irvine, L. Halscheidt, 2014: Reduction of the air traffic's contribution to climate change: A REACT4C case study. – Atmos. Env. **94**, 616–625, DOI: 10.1016/j.atmosenv.2014.05.059.

Grewe, V., L. Bock, U. Burkhardt, K. Dahlmann, K. Gierens, L. Hüttenhofer, S. Unterstrasser, A.G. Rao, A. Bhat, F. Yin, T.G. Reichel, O. Paschereit, Y. Levy, 2016: Assessing the climate impact of the ahead multi-fuel blended wing body. – Meteorol. Z., published online, DOI:10.1127/metz/2016/0758.

Hein, R., M. Dameris, C. Schnadt, C. Land, V. Grewe, I. Köhler, M. Ponater, R. Sausen, B.B. Steil, J. Landgraf, C. Brühl, 2001: Results of an interactively coupled atmospheric chemistry – general circulation model: Comparison with observations. – Annales Geophysicae **19**, 435–457, DOI: 10.5194/angeo-19-435-2001.

Köhler, M.O., G. Rädel, O. Dessens, K.P. Shine, H.L. Rogers, O. Wild, J.A. Pyle, 2008: Impact of perturbations to nitrogen oxide emissions from global aviation. – J. Geophys. Res. Atmos. **113**, D11305, DOI: 10.1029/2007JD009140.

Koch, A., 2013: Climate impact mitigation potential given by flight profile and aircraft optimization. – Ph.D. thesis, Hamburg University of Technology (TUHH).

Koch, A., B. Lührs, F. Linke, V. Gollnick, K. Dahlmann, V. Grewe, U. Schumann, T. Otten, M. Kunde, 2012: Climate-compatible air transport system, climate impact mitigation potential for actual and future aircraft. – In: Sausen, R., S. Unterstrasser, A. Blum: (Eds.), Proceedings of the 3rd International Conference on Transport, Atmosphere and Climate (TAC-3), number ISSN 1434-8454. – Forschungsbericht DLR-FB–2012-17, Deutsches Zentrum für Luft- und Raumfahrt.

Lammering, T., E. Anton, K. Risse, K. Franz, R. Hoernschemeyer, 2011: Gains in fuel efficiency: Multi-stop missions vs. laminar aircraft. – In: 11th Aviation Technology, Integration, and Operations (ATIO) Conference, Virginia Beach, VA, USA, American Institute of Aeronautics and Astronautics.

Langhans, S., F. Linke, P. Nolte, H. Schnieder, 2010: System analysis for future long-range operation concepts. – In: 27th Congress of the International Council of the Aeronautical Sciences (ICAS), Nice, France.

Langhans, S., F. Linke, P. Nolte, V. Gollnick, 2013: System analysis for an intermediate stop operations concept on long range routes. – J. Aircraft **50**, 29–37, DOI: 10.2514/1.C031446.

Lee, D., G. Pitari, V. Grewe, K. Gierens, J. Penner, A. Petzold, M. Prather, U. Schumann, A. Bais, T. Berntsen, D. Iachetti, L. Lim, R. Sausen, 2010: Transport impacts on atmosphere and climate: Aviation. Transport Impacts on Atmosphere and Climate: The {ATTICA} Assessment Report. – Atmos. Env. **44**, 4678–4734, DOI: 10.1016/j.atmosenv.2009.06.005.

Lee, D.S., D.W. Fahey, P.M. Forster, P.J. Newton, R.C. Wit, L.L. Lim, B. Owen, R. Sausen, 2009: Aviation and global climate change in the 21st century. – Atmos. Env. **43**, 3520–3537, DOI:10.1016/j.atmosenv.2009.04.024.

Linke, F., 2008: Trajectory Calculation Module (Part I: VNAV). Internal report, Deutsches Zentrum für Luft- und Raumfahrt.

Linke, F., 2016: Ökologische Analyse operationeller Lufttransportkonzepte. – Forschungsbericht dlr-fb–2016-10, Hamburg University of Technology (TUHH), ISSN 1434-8454.

Linke, F., S. Langhans, V. Gollnick, 2011: Global fuel analysis of intermediate stop operations on long-haul routes. – In: 11th Aviation Technology, Integration, and Operations (ATIO) Conference, Virginia Beach, VA, USA, American Institute of Aeronautics and Astronautics.

Linke, F., S. Langhans, V. Gollnick, 2012: Studies on the potential of intermediate stop operations for today's airlines. – In: 16th Air Transport Research Society (ATRS) World Conference, Tainan, Taiwan.

Lührs, B., 2013: Erweiterung eines Trajektorienrechners zur Nutzung meteorologischer Daten für die Optimierung von Flugzeugtrajektorien. – Master's thesis, Hamburg University of Technology (TUHH).

Lührs, B., M. Niklass, C. Froemming, V. Grewe, V. Gollnick, 2016: Cost-benefit assessment of 2d and 3d climate and weather optimized trajectories. – In: 16th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Washington, D.C., USA, American Institute of Aeronautics and Astronautics.

Martinez-Val, R., J. Roa, E. Perez, C. Cuerno, 2011: Effects of the mismatch between design capabilities and actual aircraft utilization. – J. Aircraft **48**, 1921–1927, DOI: 10.2514/1.C031348.

Maynard, G., P. Bearman, R. Gardner, J.E. Green, K. Morris, I. Poll, R. Whitfield, R. Wiltshire, 2015: Air travel - greener by design, annual report 2014–2015. – Technical report, Royal Aeronautical Society, London, UK.

Mouillet, V., 2013: Session 4: Bada family 4 – state of the art. – In: BADA User Group Meeting, EUROCONTROL Experimental Centre, Bretigny sur Orge, France.

Niklass, M., B. Lührs, V. Grewe, T. Luchkova, 2015: Potential to reduce the climate impact of aviation by closure of airspaces. – In: 19th Air Transport Research Society (ATRS) World Conference, Singapore.

Nuic, A., 2013: Session 4: Bada family 4 – results of bada 3 & 4 assessment within the scope of sesar wp16.3.1. – In: BADA User Group Meeting, EUROCONTROL Experimental Centre, Bretigny sur Orge, France.

Poll, D.I.A., 2011: On the effect of stage length on the efficiency of air transport. – Aeronautical J. **115**, 273–283, DOI: 10.1017/S0001924000005741.

Rädel, G., K.P. Shine, 2008: Radiative forcing by persistent contrails and its dependence on cruise altitudes. – J. Geophys. Res. Atmos. **113**, D07105, DOI:10.1029/2007JD009117

Schulte, P., H. Schlager, H. Ziereis, U. Schumann, S.L. Baughcum, F. Deidewig, 1997: NO_x emission indices of subsonic long-range jet aircraft at cruise altitude: In situ measurements and predictions. – Journal of Geophysical Research: Atmospheres (D17), 21431–21442, DOI:10.1029/97JD01526.

Schumann, U., 1996: On conditions for contrail formation from aircraft exhausts. – Meteorol. Z. **5**, 4–23.

Søvde, O.A., S. Matthes, A. Skowron, D. Iachetti, L. Lim, B. Owen, Ø. Hodnebrog, G.D. Genova, G. Pitari, D.S. Lee, G. Myhre, I.S. Isaksen, 2014: Aircraft emission mitigation by changing route altitude: A multi-model estimate of aircraft nox emission impact on o3 photochemistry. – Atmos. Env. **95**, 468–479, DOI:10.1016/j.atmosenv.2014.06.049.

Swaid, M., 2013: Entwicklung von Flugplanungsfunktionalitäten zur Flugmissionsanalyse unter realistischen operationellen Bedingungen. – Internal Report IB-328-2013-37, Deutsches Zentrum für Luft- und Raumfahrt.

Swaid, M., 2014: Entwicklung eines Routenoptimierungsalgorithmus zur Ermittlung windoptimaler Flugrouten in einem Luftverkehrsstrassensystem. – Master's thesis, Hamburg University of Technology (TUHH).