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A COMPARISON OF CLIMATE-OPTIMISED AND FUEL-OPTIMISED INTERMEDIATE STOP OPERATIONS FOR SELECTED CASE STUDIES

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Abstract

The effort of burning fuel for carrying fuel can be reduced by intermediate stop operations. Instead of performing a direct long-haul flight, the mission is interrupted by an intermediate landing for refuelling. Less fuel has to be carried, weight and thus fuel consumption can be reduced. This results in a proportional reduction of CO_2 emissions and the resulting climate impact. Earlier studies showed that in contrast to CO_2 emissions, climate impact from non-CO_2 emissions increases in general due to changed emission locations and quantities. An improvement of this concept with regards to climate mitigation potential can be achieved by (1) selecting the intermediate stop airport on climate-related criteria and (2) a limitation of cruise flight levels to reduce emissions in more climate-sensitive altitudes. We determine significant climate mitigation potentials for the climate-optimised ISO set-up and identify major differences in terms of intermediate airport location and preferable flight levels in comparison to the fuel-optimised counterpart.

Keywords: Intermediate stop operations, climate impact, non-CO_2 emissions, fuel efficiency, operational improvements (not more than 5)

1. Introduction

Air traffic operation significantly contributes to climate change. Aviation's share is estimated to be responsible for about 3.5% of the total anthropogenic radiative forcing and is the second largest contributor in the transportation sector [1,2]. Even in the context of the global COVID-19 pandemic, aviation's climate impact is expected to rise in the next decades [3]. Therefore, radical technological, operational and regulatory measures are required to limit the climate impact and achieve compliance with the Paris agreement [3]. While significant technological improvements require long development periods, operational improvements are able to realize mitigation potentials in the near future [4]. Besides CO_2 effects, non-CO_2 effects (such as from H_2O, NO_x, and contrails) contribute to about two thirds of aviation's net radiative forcing [1]. Furthermore, in contrast to CO_2 emissions, the climate impact of non-CO_2 emissions highly depends on emission location and time [5]. Consequently, operational measures aiming for fuel efficiency and reducing CO_2 emissions do not necessarily improve the total climate impact. A distinction between fuel-optimising measures targeting minimal fuel consumption and climate-optimising measures targeting minimal average temperature response (ATR) is required and will be subject to this study.

The concept of Intermediate Stop Operations (ISO) aims to reduce the stage length of a mission by performing one or more intermediate stops for refuelling. Thus, the total amount of fuel required for this mission can be reduced as shorter stage lengths allow to reduce the amount of fuel that is needed to carry the required fuel on the respective mission. In a fuel-optimised set-up of ISO, flight altitudes for the first leg are typically above the non-stop mission, as lighter aircraft weights lead to higher fuel-optimal cruise altitudes (as displayed in Figure 1). Consequently, emissions are released in higher altitudes what implies higher climate impacts. Based on previously achieved research results, we hypothesize, that adjustments to the known ISO concepts will enable overall climate mitigation potentials. This study contributes to state-of-the-art research by (1) defining a climate-optimised set-up of ISO (2) estimating the climate mitigation potential of climate-optimised ISO and (3) providing a comparison between fuel-optimised and climate-optimised configurations for selected missions.

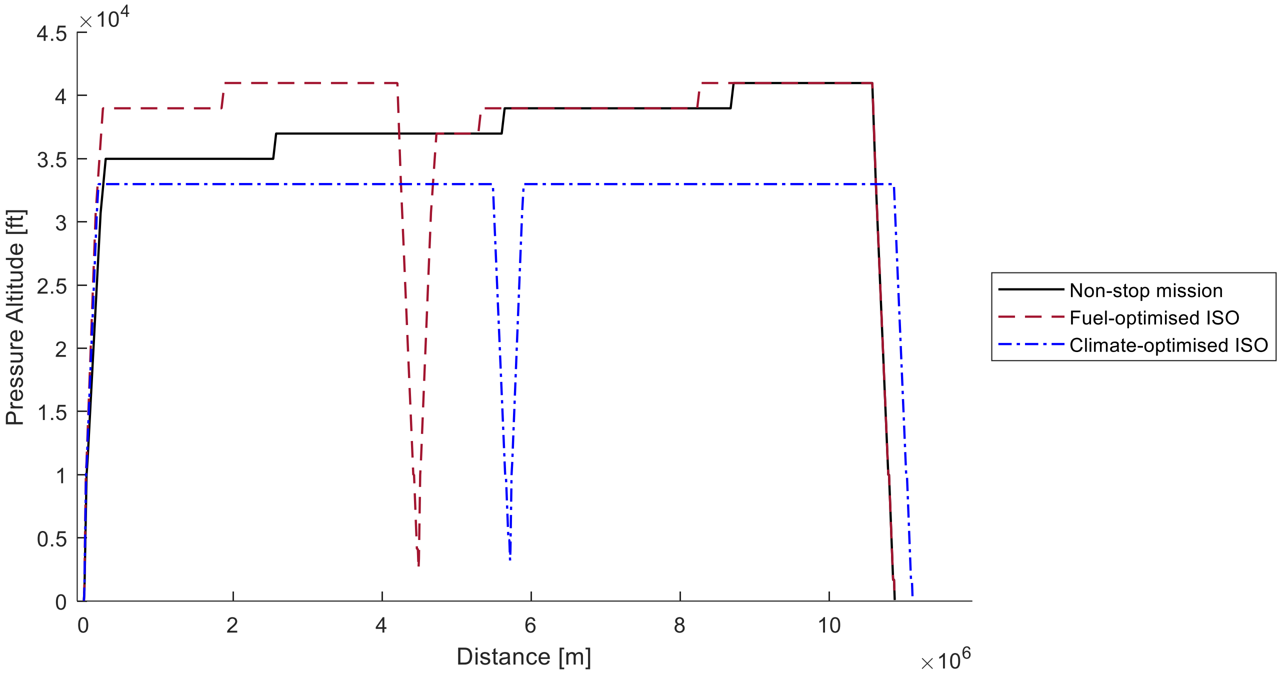

Figure 1 – Altitude profile of an exemplary flight for the reference case of a fuel-optimal non-stop flight, fuel-optimised ISO, and climate-optimised ISO.

1.1 Previous Research

Previous research has focused on improvements in fuel efficiency: Besides technical and design measures such as optimised engines or aircraft geometries, operational approaches considering aircraft speed, cruise altitudes and aircraft weight enable a reduction of fuel consumption [6]. While technical adjustments are typically associated with long development periods until implementation and realisation of benefits, operational improvements are expected to be realised quickly and thus play an important role in the next decades [4].

One of these operational measures is described by ISO, where aircraft mass is reduced by fuel reduction, making up a major share of an aircraft's take-off mass. If an aircraft is refuelled during a long-haul mission, stage lengths are reduced and also the amount of fuel required along the mission. Thus, fuel efficiency improves, what has been proved in previous work of research [6-9]: Depending on flight length, wind conditions, and aircraft design range, fuel saving potentials between 7% and 28% are identified on a single mission basis, whereas the global potential is estimated to be around 5% in the case of one intermediate refuelling stop. Studies incorporating several stops and an aircraft re-design to the shorter stage lengths estimate a fuel saving potential between 17% and 50% [9-12]. While ISO is beneficial to reduce fuel burn for a large share of long-haul flights, cost savings are strongly dependent on the selected city pair, fuel cost, wind conditions, and crew criteria [13]. Furthermore, an implementation is associated with significant adjustments in the air traffic system, so that costs and benefits need to be evaluated comprehensively from the airlines' perspective. Martinez-Val [14] found that improvements in direct operating cost (DOC) are smaller than reductions in fuel consumption due to increased flight times. This is particularly relevant for set-ups with more than two stages, as only marginal improvements are achieved in comparison to two stages [9]. Moreover, a reduction of fuel consumption and CO_2 emissions by implementing ISO is not necessarily associated with a reduction of the climate impact. This is mainly due to an upward shift of emission altitudes compared to the reference case (Figure 1). Therefore, altitude dependent climate impact from non-CO_2 emissions such as NO_x, H_2O and contrails are expected to rise in this context [15,16]. Linke et al. [16] have shown that increased climate impact from non-CO_2 emissions overcompensate climate effects from CO_2 emissions for fuel-optimised ISO, thus this set-up is not beneficial from a climate mitigation perspective. Alvarez & Santos [17] investigated the inclusion of selected ISO routes in an airline network and found a small climate mitigation potential of 0.1%. However, we expect additional climate mitigation potentials of ISO if a climate-optimised set-up is implemented.

1.2 Scope and structure of this study

Goal of this study is to define an ISO set-up that is beneficial to the climate and to compare this to the fuel-optimal specification. Fuel-optimised ISO is typically determined by a fuel-optimal refuelling airport, i.e. one that is as close as possible to the centre point of the great circle connection, and characterized by fuel-optimal flight levels, i.e. step climbs are performed. To reduce aviation's climate impact with an implementation of ISO, we consider the following adjustments: (a) the selection of refuelling airport is based on minimum average temperature response over 100 years (ATR100) instead of minimum fuel consumption and (b) step climbs are avoided and climate-optimised flight altitudes are selected. In the course of this, altitude and location dependent effects of non-CO_2 emissions can be included. Fuel efficiency improvements and climate mitigation potentials are derived from a comparison of fuel- and climate-optimised ISO with a non-stop reference case. Results can be compared in terms of fuel consumption, flight time, detour, emission quantities and ATR100. The results are presented by means of selected case studies. At first, we analyse major differences between climate-optimised and fuel-optimised ISO in terms of location of intermediate stop airport and selected flight levels as well as changes in major parameters such as fuel burn or ATR100. Secondly, we investigate the impact of exchanging long-haul aircraft with short-haul aircraft on intermediate stop missions and the additional potential of more than one intermediate stop for an ultra-long-haul mission. Finally, an outlook on a full European scale is provided.

2. Methodology & Materials

To model the different parameters for comparison, the following work flow is applied to calculate climate and non-climate characteristics of the selected missions: Based on location and altitude of origin and destination airport, Reduced Emission Profiles previously calculated by the Trajectory Calculation Module (TCM) developed at the German Aerospace Center (DLR) are deployed to determine four-dimensional trajectories including fuel flow at every simulated point along the great circle trajectory [18]. The resulting trajectories are the basis for gridded emission inventories calculated with DLR's Global Air traffic emission distribution laboratory (GRIDLAB) [18]. These are fed into DLR's climate chemistry response model AirClim, so that different ISO scenarios can be compared to one another as well as the non-stop reference case along fuel burn, trip time and ATR [19].

2.1 Selection of flights & initial situation

Investigated missions are selected from a full European flight plan in 2018 in accordance with the defined scope of the ClimOP project[1], which defines the context of this study. Input data is provided by a European flight plan from Sabre Market Intelligence data base [20]. As ISO implementation is only expected to be beneficial for flight distances of more than 2,500 nautical miles (NM) [21], only long-range missions performed with wide-body aircraft are considered. For each analysed combination of origin and destination airport (OD pair), a set of possible intermediate airport candidates is identified. These are derived from a global set of airports [22]. We preselect possible refuelling airports as a function of [7,16]:

- the detour associated with the respective airport relative to the great circle. That means, only those airports are considered, that do not extend the total mission length by more than the defined limit in comparison to the great circle distance of the non-stop reference mission.
- the offset of the respective airport, describing its eccentricity from the centre point of the great circle connection. For example, an offset factor of 67% describes an ISO mission where the longer leg covers two thirds of the mission length.

Furthermore, a preselection is performed according to a defined grid to further reduce computational efforts. The meridional resolution of this grid is set to 30°, respectively 15° for northern mid latitudes

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[1] https://www.climop-h2020.eu/

where most of the traffic occurs [19], and a longitudinal resolution of 30° is assumed. From each of the defined grid cells, the airport with the smallest detour factor is selected.

In addition to considerations of different possible refuelling airports, different cruise flight levels are included in this analysis to consider additional climate mitigation potentials from altitude dependent non-CO_2 emissions. Besides a fuel-optimal altitude profile, where step climbs are performed to enhance fuel efficiency, we additionally calculate the investigated metrics for missions at constant flight levels from the range between 29,000ft and 37,000ft.

2.2 Trajectory simulation

Calculation of trajectories for reference case and ISO missions builds the basis for assessing and comparing climate and non-climate metrics. For this purpose, DLR's TCM is applied to create standardised reduced emission profiles. Within the TCM, the aircraft is considered as a mass point, whose speeds, accelerations, and altitude changes are described with a set of simplified equations of motion (Total Energy Model, TEM). A forward integration in combination with engine data enables calculation of fuel flow and changes in aircraft state over discrete time intervals [18,23]. To ensure efficient calculations for a large set of flights, reduced profiles are applied [18]. For this purpose, one-dimensional and non-georeferenced trajectories of different flight lengths in 100 NM steps are calculated for every possible combination of considered aircraft type and flight altitude and stored into a database. This results in standardised and location independent profiles of altitude and fuel flow over distance and flight time. The resulting reduced trajectories can be adjusted successively to match the exact great circle distance between the two connected airports as well as the respective airports' elevation. Cruise, climb and descent segments are adjusted accordingly.

To ensure a comparability and scalability of results to a full European scale in accordance with the ClimOP project, we assume great circle connections between the respective airports and apply average atmosphere conditions in terms of International Standard Atmosphere (ISA), i.e. no winds are considered in this analysis. As an annual flight plan is investigated, day-specific airspace restrictions and time-dependent meteorological conditions are excluded from the study. Furthermore, we assume an average European load factor of 84% [24]. Aircraft performance data is derived from Base of aircraft data version 4 (BADA4) as provided by EUROCONTROL [25], which also provides applied speed schedules and optimum altitudes.

2.3 Emissions calculation

Subsequently, GRIDLAB is applied to generate three-dimensional emission inventories for each of the considered flights [18]. Based on fuel flow and atmospheric boundary conditions along the trajectories, we calculate emissions of CO_2 and non-CO_2 species. In this context, CO_2 and H_2O emissions are assumed to be proportional to fuel flow, whereas NO_x emission quantities are calculated with DLR's fuel flow correlation method and emission indices obtained engine emission database provided by International Civil Aviation Organization (ICAO) [26,27]. Emissions caused by taxiing and the take-off itself are considered following the landing and take-off (LTO) cycle from ICAO and the reference emission indices from ICAO engine emission database [27]. Additional emissions and trip times are added for the on-ground time in accordance with the LTO cycle (19 minutes for taxi out, 7 minutes for taxi in, 0.7 min in engine take-off mode) [27]. Finally, the emission profile is projected on the great circle between the connected airports, and the calculated emission amounts are distributed spatially on a numerical grid with a horizontal resolution of 0.25° (latitudinal and longitudinal) and a vertical resolution of 1000ft. On this basis, climate metrics can be calculated in a next step.

2.4 Climate impact modelling

The GRIDLAB results for all relevant grid cells in terms of longitude, latitude, fuel burn, nitroxide emissions, and the aggregated distance for the derivation of contrail effects are fed into AirClim via a Remote Component Environment [28] to calculate climate response metrics. AirClim [19,29] is a climate-chemistry response model that enables to calculate the climate impact resulting from flight emissions. In this context, near surface temperature changes caused by emission species CO_2, H_2O, contrails as well as changes in methane and ozone induced by NO_x emissions are considered. These concentration changes and the resulting radiative forcing is described as a function of latitude and altitude, that has been pre-calculated for normalised emissions. A climatological approach is selected where the calculated climate impact represents a mean over all weather situations.

We focus our analysis on ATR100, which is the average near surface temperature change over 100 years. In contrast to emission quantities of different species and other existing climate metrics like Global Warming Potential or Radiative Forcing (RF), ATR enables a comparison of the climate impact of different scenarios in terms of temperature change by incorporating dynamics of the earth climate system and reducing the dependency on the time horizon at the same time [30,31]. We apply a future emission-scenario-based ATR, typically referred to as F-ATR [31]. Climate mitigation potential in the following is described by a reduction in F-ATR100 caused by an implementation of the operational improvement in comparison to the reference scenario.

In this context, we assume an implementation of ISO concepts on the selected missions in 2025, so that simulations run until 2125 to cover the 100-year period required for ATR100. In contrast to previously published research, e.g. by Linke et al. [16], we apply state-of-the-art background emissions from aviation as described by the business as usual (BAU) scenario in Grewe et al. [3], which assumes an increase in fuel efficiency due to technology improvements but excludes carbon-offsetting efforts or additional specific aims regarding the climate impact. For background emissions in terms of CO_2 and CH_4, we assume a development according to Representative Concentration Pathways (RCP) 4.5, which is described as an intermediate scenario with a resulting RF of 4.5 Wm^{-2} in the year 2100 [32].

3. Results

In the following, results will be presented by means of selected case studies. The general potentials of ISO and a comparison along fuel- and climate-optimised configuration is described in the first case study. Subsequently, additional mitigation potentials due to a replacement with aircraft designed for shorter ranges and more than one refuelling stop are analysed, before an outlook to a scenario of multiple flights is given.

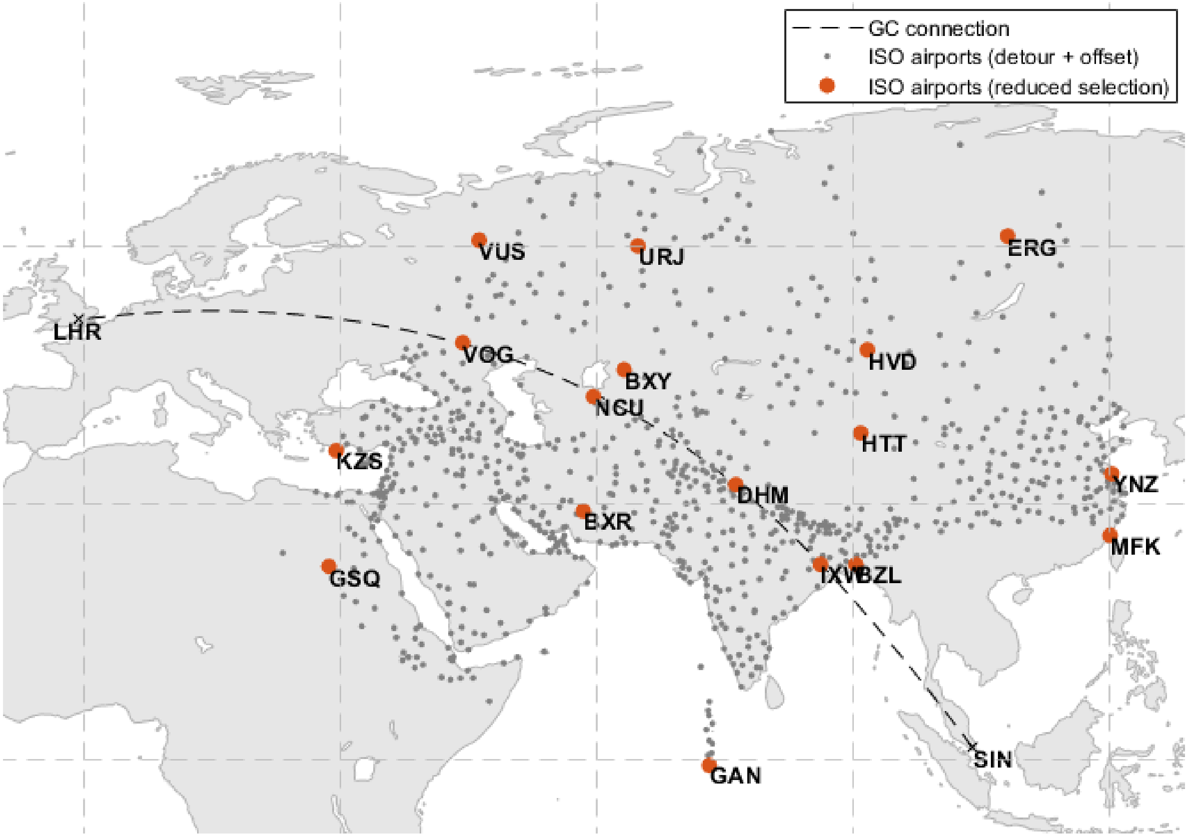

Figure 2 – Location of pre-selected intermediate stop airports according to the described methodology based on a sample of possible airports according to detour and offset for a single-mission example from Singapore to London.

3.1 Single mission case-study

To illustrate the major differences between fuel- and climate-optimised ISO and determine their potential, a mission from Singapore Changi Airport (SIN) to London Heathrow (LHR) with an Airbus A380 is examined. This flight covers approx. 7 billion available seat kilometres (ASK) in 2018, which makes it the most relevant one from the selected flight plan in terms of ASK. In this case, a self-substitution of aircraft is assumed, i.e. both ISO and direct mission are performed with the selected aircraft type. An implementation of ISO is therefore possible without adjustments of the operator's fleet.

A pre-selection of candidate airport is performed as displayed in Figure 2. In a first preselection step, we limit the selection of airports from the global sample to those with an additional detour factor below 20% and an eccentricity below 75%. In a second step, the sample is reduced according to described grid resolution. This results in 17 considered ISO airports that are distributed over Asia, Eastern Europe, North East Africa and the Middle East with detours ranging from additional 0% to 18%, and eccentricities between 51 and 75 %. Based on the selected airport, climate and non-climate metrics are calculated according to the previously described modelling chain. An extract of the results is displayed in Table 1. We confirm previous research results, in a way that ISO can lead to significant fuel savings if a suitable refuelling airport is selected. Furthermore, we validate that fuel-optimised ISO is not beneficial from a climate perspective. The fuel-optimised mission with an intermediate landing at Kangra Airport in India (DHM) is associated with an increase in ATR100 by 6%. Thus, a reduction in fuel-proportional CO_2 effects is overcompensated by non-CO_2 effects if fuel-optimal step climbs are assumed. Even the best ISO airport from a climate perspective with a refuelling stop in Kastelorizo (Greece, KZS) leads to an increase in ATR100 in comparison to the reference case by almost 2%.

Table 1 – Changes of selected climate and non-climate metrics in comparison to the non-stop reference case in dependence of selected ISO airport assuming fuel-optimal flight levels

				Change relative to the non-stop reference case		
Refuelling airport	**Lat | Lon**	**Detour**	**Offset**	**Fuel**	**Time**	**ATR100**
Kangra Airport, India (DHM)	58.7 | 32.2	0.0%	58.7%	- 6.1%	+ 4.8%	+ 6.3%
Nukus Airport, Uzbekistan (NCU)	58.4 | 42.5	0.0%	58.4%	- 5.9%	+ 4.9%	+ 5.2%
Bam Airport, Iran (BXR)	51.4 | 29.1	2.2%	51.4%	- 3.8%	+ 6.8%	+ 5.4%
Volgograd Airport, Russia (VOG)	48.8 | 44.3	0.0%	71.0%	- 4.9%	+ 4.9%	+ 3.9%
Kastelorizo Airport, Greece (KZS)	36.1 | 29.6	5.1%	74.4%	+ 1.4%	+ 9.8%	+ 1.8%

If we additionally incorporate different flight levels as described above, we find significant mitigation potentials in terms of ATR100 (as displayed in Table 2). If step climbs are avoided and a constant flight level of 35,000ft is assumed, we see a reduction in ATR100 of 27.6% for the climate-optimised ISO airport at Nukus, Uzbekistan (NCU). However, this is not associated with improved fuel efficiency compared to the reference case. The fuel-optimised solution at this flight level reduces fuel burn by 0.1% and ATR by 27.2% with a refuelling stop at DHM. In comparison to a direct flight at the selected constant flight level, fuel burn can be reduced by 5.3% with ISO. With an additional inclusion of flight level reductions, we obtain further reductions in ATR100 but increases in fuel consumption. Mitigation potentials of up to 45.7% can be achieved (Table 2).

Furthermore, we find that not only climate-optimised and fuel-optimised ISO airports are not identical but also that climate-optimised airports can vary with the selected flight level. The fuel-optimised airport is associated with a minimum of offset and detour, i.e. located as close as possible to the centre of the great circle connection in the absence of wind. Furthermore, higher elevations of ISO airports can be beneficial (altitude 770m at DHM, 76m at NCU) in this context. While the fuel-optimised airport in this case study does not change with varying flight altitudes and is always located at DHM, climate-optimised airport changes with flight level.

Table 2 – Changes of selected climate and non-climate metrics for fuel- and climate-optimised ISO, for selected flight levels and ISO airports in relation to the non-stop reference case

					Change relative to the non-stop reference case		
Refuelling airport	**Lat | Lon**	**Detour**	**Offset**	**Flight level [ft]**	**Fuel**	**Time**	**ATR100**
Kangra Airport, India (DHM)	58.7 | 32.2	0.0%	58.7%	35000	- 0.1%	+ 4.1%	- 27.2%
				29000	+ 8.9%	+4.7%	- 45.3%
Nukus Airport, Usbekistan (NCU)	58.4 | 42.5	0.0%	58.4%	35000	+ 0.0%	+4.2%	- 27.6%
				29000	+ 9.1%	+ 4.9%	- 45.3%
Bam Airport, Iran (BXR)	51.4 | 29.1	2.2%	51.4%	35000	+ 2.1%	+ 6.2%	- 25.6%
				29000	+ 11.1%	+ 6.8%	- 45.7%

From the defined set of missions described by refuelling airport as well as selected flight level, we can identify overall fuel-optimised and climate-optimised scenarios: On one hand, from a fuel efficiency perspective, an intermediate stop at DHM and continuously adjusting the flight altitude to fuel-optimal levels during the mission represents the optimal scenario. On the other hand, a refuelling stop at BXR and a reduction of cruise flight levels to 29,000 ft is optimal from a climate mitigation perspective within the set constraints of the study. Figure 3 illustrates the changes in contribution of different emission species to ATR100 for the different optimisation goals. For the fuel-optimised case, we see a reduction in CO_2 induced ATR100 by 6 % in accordance with the reduction in fuel consumption. Nevertheless, overall climate response increases as a majority of non-CO_2 emissions cause a raise in ATR100. Especially contrail and H_2O effects increase whereas changes in NO_x induced warming (O_3, CH_4 and primary-mode ozone, PMO) can be neglected, as they approximately compensate each other. In contrast to that, overall ATR100 is considerably reduced in the climate-optimised scenario, which is mainly caused by a reduction in contrail, nitroxide and water vapor induced effects, that overcompensate increased CO_2 impacts due to an increased fuel consumption.

We conclude that a broad set of parameters influences the optimal ISO configurations in this case: (a) The selection of intermediate stop airports is dependent of its location in terms of the associated offset, detour and its elevation. From a climate-optimisation perspective, additional potential can be achieved if emissions are shifted to less climate-sensitive areas due to lateral route adjustments. (b) The selected flight altitude influences both fuel consumption and climate impact. While fuel efficiency is typically optimal if the right step climbs are performed and decreases with lower cruise altitudes, an additional flight level reduction is beneficial from a climate perspective. In this context, ATR reduction effects from ISO and reduced cruise altitudes overlap. Hence, scenarios can be identified where additional fuel consumption from flying lower can be compensated by ISO so that fuel efficiency and climate impact improve (e.g. for an intermediate stop at DHM and a cruise altitude of 35,000ft).

3.2 Exchange of aircraft types

In previous research, additional fuel efficiency gains from ISO were achieved by a re-design of aircraft types. Typically, the replacement aircraft is optimised towards a shorter design range. As we exclude extensive technological changes from this study on operational improvements, we apply existing aircraft types in this case, i.e. we substitute the reference wide-body aircraft with an aircraft optimised for shorter ranges. As not all combinations of origin, destination and intermediate stop airport can be connected by these aircraft types, a further selection of ISO airports is implicitly performed.

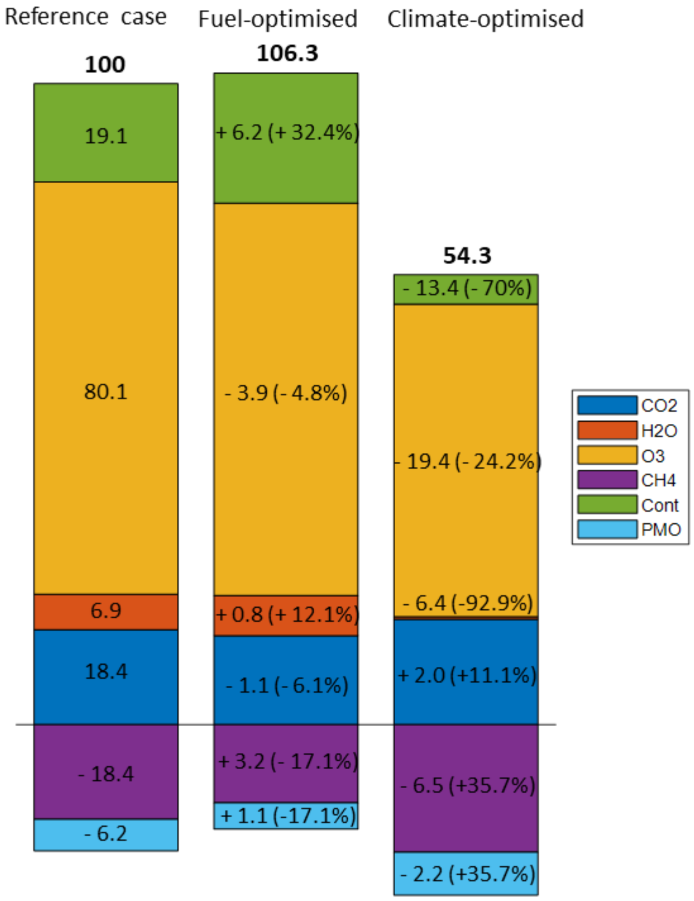

Figure 3 – ATR100 contribution of different emission species for reference case (normalised to 100), as well as fuel-optimised and climate-optimised ISO relative to the reference case

In the following, we present results for a selected set of flights from the above mentioned European long-haul flight plan, where we assume benefits from ISO implementation. This context, we consider a constant flight level of 35000ft in the ISO case and fuel-optimal step-climbs in the reference case. Looking at a flight from LHR to Dubai International Airport (DXB) where the reference aircraft (Airbus A380) is replaced by an Airbus A321 with a significantly smaller design range, we observe substantial reductions in fuel consumption (- 73.2%) and in ATR100 of (- 81.9%) compared to the non-stop case performed by the reference aircraft. Nevertheless, it needs to be considered that if the same payload is carried from origin to destination, a single-aisle aircraft needs to perform four times the number of flights on the corresponding OD pair in this case. Consequently, results in terms of required fuel and caused ATR100 need to be scaled up by the correct factor to cover the equivalent payload, what is summarized for a selected set of flights in Table 3.

Table 3 – Fuel burn and ATR100 relative to the non-stop reference case on selected missions at a constant flight level of 35,000ft

Origin	Destination	ISO	Aircraft type	Fuel	ATR100
Dubai International Airport, United Arab Emirates (DXB)	London Heathrow, United Kingdom (LHR)	Kastamonu Airport, Turkey (KFS)	4x A321-100	- 2.0%	- 25.1%
			A380-800	+ 9.0%	- 37.0%
Heathrow Airport, London, United Kingdom (LHR)	Los Angeles International Airport, United States (LAX)	Quaqtaq Airport, Canada (YQC)	3x 737-300	+ 50.2%	+ 79.5%
			787-9	+ 3.5%	- 15.0%
John F. Kennedy International Airport, New York, United States (JFK)	Heathrow Airport, London, United Kingdom (LHR)	Gander International Airport, Canada (YQX)	4x 737-300	+ 17.9%	+ 22.4%
			747-800	+ 5.4%	- 24.9%

Depending on the selected mission and the corresponding reference aircraft, we see that a replacement is not necessarily beneficial, though there are cases where both fuel consumption and ATR100 can be reduced. Based on that, we assume that ISO advantages in this case depend on the selected exchange aircraft, the reference aircraft as well as the stage length of the corresponding mission. A more detailed analysis of the underlying correlations should be the focus of future research. Nevertheless, there are optimisation potentials through substitution of aircraft types even when missions have to be performed multiple times to assure the same amount of payload to be covered.

3.3 Multi-intermediate stop operations

To investigate the implications of more than one intermediate stop, we investigate an ultra-long-haul route from the underlying European flight plan from LHR to Perth Airport (PER) covered by a Boeing 787. The mission length of approx. 7,870 NM is significantly longer than the average of the flight plan. Based on the assumption that ISO can be beneficial for distances from 2,500 NM on, several ISO stops could have a positive impact in this case, so that we investigate a multi-stop ISO concept for the selected case study in the following.

To investigate multi-stop ISO operations, the pre-selection of refuelling airport candidates needs to be adjusted: we keep the allowed detour caused by the intermediate landing by additional 25% but adjust offset factors so that all three legs account between 10% and 60% of the total distance. The set of possible airports is further reduced according to the resolution as described above (Chapter 2.1).

Table 4 – Change in fuel consumption and ATR100 for one or two intermediate stops on an exemplary ultra-long-haul mission from LHR to PER with a Boeing 787 relative to the non-stop reference flight

ISO airports	Detour	Flight level [ft]	Fuel	ATR100
Fuel-optimised selection of two ISO airports	+ 1.8%	fuel-optimal	- 6.3%	+ 2.1%
Climate-optimised selection of two ISO airports	+ 8.6%	fuel-optimal	+ 0.0%	- 4.2%
Climate-optimised selection of two ISO airports	+ 8.6%	35000	+ 9.3%	- 30.7%
Climate-optimised selection of two ISO airports	+ 2.1%	31000	+ 13.1%	- 67.7%
Fuel-optimised single ISO airport	+ 0.0%	fuel-optimal	- 7.1%	- 1.8%
Climate-optimised single ISO airport	+ 0.8%	fuel-optimal	- 6.3%	- 1.9%
Climate-optimised single ISO airport	+ 0.8%	35000	+ 1.5%	- 30.5%
Climate-optimised single ISO airport	+ 0.8%	31000	+ 11.4%	- 66.6%

From the selected set of intermediate airports for the ultra-long-haul mission from LHR to PER, we identify significant mitigation potentials in terms of fuel consumption and ATR100 for an implementation of two intermediate stops. However, results need to be put into the context of a comparison with one-stop over operations: We find that climate mitigation potentials can be enhanced by more than one intermediate stop, but for the selected sample of flights and candidate airports, single ISO leads to higher fuel efficiency gains. Nevertheless, additional fuel consumption and ATR100 reduction can be balanced, for example two-stop operations at a fuel-optimal flight level can already mitigate the climate impact (- 4.2% in ATR100) without additional fuel required.

3.4 Outlook on an aggregated scenario

The results achieved in the previous chapters prove fuel efficiency gains as well as climate mitigation potentials from ISO depending on the configurations of the concept. To derive general conclusions, it needs to be investigated if this holds true for a broader set of flights. For this purpose, we analyse a randomly selected set of 630 European long-range flights from 2018 to provide an outlook on a broader scale. Thereby, we cover approx. 13% of the ASK of the full annual European flight plan, so we can rather assume a more representative traffic sample. We apply the workflow as described in section 2 equivalent to the single case study in chapter 3.1 and achieve results as displayed in Table

5.

The results of the aggregated flight plan confirm, what has been shown for the single case study: While fuel-optimised ISO increases fuel efficiency (in this sample by 2%), this set-up is not beneficial to the climate. Reduced impacts from CO_2 emissions are overcompensated by additional climate impact of non-CO_2 emission species. Especially water vapor (+ 11.1%) and nitroxide induced effects (+ 2.4%) increase while contrail and CO_2 impacts are reduced. For about a half of the flights (47.4%), fuel efficiency is increased by ISO. By contrast, a climate-optimised configuration leads to an increase in fuel consumption and flight time but also comes along with significant reduction potentials in ATR100 (- 39.7%). All of the selected flights' climate response can be improved by an implementation of a climate-optimised ISO concept. In comparison to the non-stop reference case, climate impact from CO_2 emissions increases (+ 16.4%) while the climate impact from all considered non-CO_2 species decreases significantly (by - 89.5% for water vapor, - 48.3% for nitroxides, and – 52.4% for contrails). However, it needs to be noted that these mitigation potentials are not only caused by ISO but also by shifting emissions to lower more climate-friendly altitudes itself.

Table 5 – Changes in climate and non-climate metrics for fuel-optimised and climate-optimised ISO scenarios relative to the non-stop reference case

	ISO share	Detour	Fuel	Time	ATR100
Fuel-optimised ISO	47.4%	+ 0.1%	- 2.0%	+ 3.5%	+ 0.7%
Climate-optimised ISO	100%	+ 3.4%	+ 16.4%	+ 9.8%	- 39.7%

A comparison of both set-ups for selected sample of flights shows that the climate-optimised case is associated with higher detours (+ 3.4% compared to + 0.1%) and offset factors (66.1% compared to 55.7%). Furthermore, refuelling airports closer to the equator are preferred in the climate-optimised case (average latitude of 36.0 compared to 45.8 degrees), while no significant difference can be observed in terms of longitude for the selected sample.

4. Discussion

Our results are in line with previously conducted research in terms of fuel-optimised ISO [6-9]: We confirm a fuel saving potential of ISO. In our case, we find that fuel efficiency improves by approx. 6% for the selected case study from Singapore to London and 2% for a sample of 630 European long-range flights. This example also shows that the fuel-optimised configuration is not necessarily beneficial to the climate, as ATR increases, in accordance with [16]. Furthermore, we present a new concept of climate-optimised ISO and confirm that there are configurations that enable ATR100 mitigation in the course of ISO. This can be achieved by adjusting the flight level and the selection of intermediate stop airport. In contrast to fuel-optimised configurations, climate-optimised ISO generally aims for lower flight levels on the one hand and accepts higher detours on the other hand, if location of the selected airport is beneficial to the climate in return. These correlations also remain valid for a broader sample of flights, for which we identify a reduction potential in ATR100 by approx. 40%. Additionally, we add to existing research [10-12] that substitution with aircraft optimised for shorter distances as well as multi-stop ISO can provide additional fuel efficiency or climate mitigation gains in dependence of mission characteristics.

It has to be considered that the design of this study does not present climate-optimal solution per OD pair according to the preselection process performed. While our set-up ensures efficient calculations for a large set of flights or even a global flight plan, thereby it cannot be assured that a climate-optimal airport or flight level is selected. It is possible that even higher mitigation potentials can be achieved if a different airport from the same grid cell would be associated with a smaller climate response. Furthermore, we exclude a consideration of capacities and facilities at possible refuelling airports. A more detailed analysis in how far the selected airports can actually handle the required amount of additional starts and landings due to ISO requires a separate analysis.

Besides the above-mentioned limitations resulting from this study's definition of research subject and boundary conditions, further uncertainties are incorporated in the modelling process itself. Taken assumptions in the trajectory modelling process such as flight performance data from BADA 4, great circle assumptions and an average load factor are estimated to lead to moderate inaccuracies. Further uncertainties may derive from calculating emissions with fuel flow correlation methods and climate impact modelling itself.

In addition, it is necessary to discuss implementation barriers resulting from a climate-optimised ISO concept: As climate-optimised ISO is per definition not necessarily equivalent to a fuel-optimised set-up, fuel consumption can even rise in a climate-optimised scenario. This in turn increases fuel cost and also possible required offsetting cost for the resulting proportional increase in CO_2 emissions. Both defined ISO concepts lead to an increase in flight time by resulting detours but also by the additional start and landing times as well as times for taxiing and the refuelling process itself, what further increases DOC. This strongly limits implementation attractiveness from an operator's point of view under given limitations and regulations. These barriers can be reduced by incorporating allowed limits of additional fuel and time into the evaluation process and derive pareto-fronts accordingly. This would help to find a compromise between climate benefits and costs of implementing this measure. Furthermore, implementation of ISO significantly influences an airline's network. Longer flight times require adjustments to the network. Besides obstacles from an operator's perspective, additional departures and arrivals and a shift of flights to more climate-friendly altitudes can further impede an implementation of ISO as airports and airspaces will experience higher utilisation and possibly congestion.

5. Conclusion

In summary, we confirm our initially introduced hypothesis: The concept of ISO is not only eligible to reduce fuel consumption of long-range flights and the resulting CO_2 emissions. It can also be adjusted towards a climate mitigation focus taking both CO_2 and non-CO_2 emissions into account. In the course of this study, we present a methodology on how to define climate-optimised ISO operations and in how far it differs from the fuel-optimised set-up. In this context, we show that avoiding high and thus climate sensitive cruise altitudes enables a reduced warming impact while limiting additional fuel consumption at the same time. Furthermore, a selection of refuelling airports according to the associated climate impact additionally enhances mitigation potentials. If routes can be shifted to less climate-sensitive areas by stopping at a certain intermediate stop airport additional mitigation potential can be achieved. Hence, intermediate stop airport location and altitude influence the set-up of a climate-optimised route network in a way that additional detours can even be beneficial from a climate mitigation point of view. Moreover, we find that both fuel efficiency and climate mitigation potentials can be extended by a replacement of long-range aircraft with medium-range aircraft and by multi-stage ISO. In what way the different outcomes can be combined into an optimal set-up of climate-optimised ISO should be subject to further research as well as implementation consequences for stakeholders involved in the air traffic system in terms of cost, airspace and airport utilisation and safety. Also, results should be confirmed on a global scale.

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7. Copyright Statement

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