Reducing the climate impact of flight trajectories considering network effects

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***Abstract*—To mitigate the climate impact of aviation, operational approaches can contribute in the short-term before technological innovations are available on a large scale. Adjusting flight trajectories both temporally and spatially appears promising to reduce non-CO_2 climate effects in particular. However, adaptations to these trajectories influence the air traffic network leading to implementation restrictions. This study addresses the trade-off between climate mitigation and network stability for a case study in the European airspace. Results show high climate mitigation potentials of contrail effects for vertical trajectory adaptations. Network effects in terms of traffic demand in individual airspaces due to trajectory shifts are visible but appear to be manageable when focusing on high-impact flights.**

***Keywords*—air transport operations, non-CO_2 effects, climate mitigation, trajectory adaptation, airspace capacity, air traffic management**

I. INTRODUCTION

Aviation's contribution to net anthropogenic effective radiative forcing is estimated around 3.5% [1]. This is not only due to effects caused by carbon dioxide (CO_2) emissions from aero engines but also due to significant non-CO_2 effects. Non-CO_2 emissions such as nitrogen oxides (NO_x), water vapor (H_2O) and aerosols lead to changes in the atmospheric radiative balance by direct greenhouse gas effects (e.g. H_2O), indirect greenhouse gas effects (e.g. NO_x-induced ozone production and methane depletion) as well as cloud effects (e.g. contrail-induced cloudiness; CiC) [2]. In comparison to CO_2, these non-CO_2 effects do not only depend on emission quantities but also vary significantly with location, time and atmospheric conditions during the emissions [1].

A broad variety of different mitigation strategies has been investigated to reduce aviation's climate impact. A recent analysis has shown, that even in context of the global COVID19 pandemic, a comprehensive set of innovative measures is required to achieve compliance with the Paris Agreement in the aviation sector [3]. Fig. 1 shows different categories of climate mitigation measures. While radical technical innovations such as new propulsion concepts, highly efficient aircraft or sustainable alternative fuels are promising in the long-run, these measures are not expected to come into effect on a large scale in the next decade. By contrast, operational measures can theoretically be implemented right away and with the current world fleet. These measures either try to reduce aviation emissions, e.g., by increasing efficiency with improved routing [4] or reducing fuel burn with innovative operational concepts [5], [6]. Alternatively, geo-temporally varying climate sensitivity can be exploited in climate optimized routing [7], [8]. For instance, flight altitudes can be changed to avoid highly climate sensitive regions of contrail formation [9], [10]. Moreover, a time shift of trajectories (temporal adaptation) can reduce the warming effect of CiC, which strongly depends on the time of day [11], [12]. Regulatory measures aim to motivate the realization of both technical and operational climate mitigation approaches by reducing the disadvantages of their implementation. For instance, new emission standards can be set or market-based approaches can be established to internalize climate cost.

The current state of literature comprises a variety of studies investigating different strategies of trajectory adaptation indicating promising mitigation potentials. However, these studies typically lack an extensive assessment of the impact on stakeholders of the air transport system. Nevertheless, these effects need to be investigated to realistically evaluate the feasibility of different measures. A significant increase in fuel burn or flight time and associated operating cost hinder a realization from operators' perspective, while a high utilization of certain less climate-sensitive airspaces reduces the probability of implementation from the network's perspective. Table I systematically summarizes recent studies on operational climate mitigation measures focusing on trajectory adaptation. While climate mitigation potentials are analyzed comprehensively

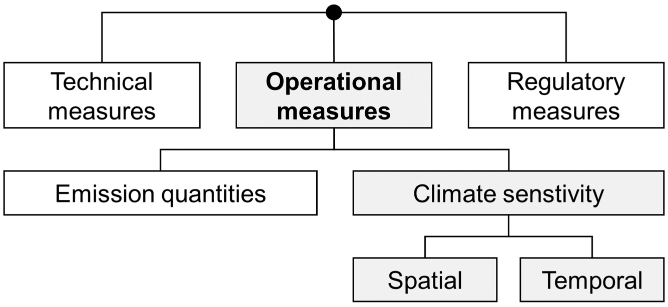

Figure 1. Climate mitigation approaches in aviation

TABLE I. REVIEW ON SELECTED RECENT LITERATURE STUDIES INVESTIGATING TRAJECTORY-RELATED CLIMATE MITIGATION MEASURES

	Measure	Climate effect	Operating cost	Network effects
Teoh et al., 2020 [9]	Small vertical diversions	Energy forcing (CiC, CO_2)	Not considered	Not considered
Lührs et al., 2021 [8]	Trajectory optimization	ATR20 (CO_2, NO_x, H_2O, CiC)	Not considered	Not considered
Meuser et al., 2022 [13]	Trajectory optimization	ATR20 (CO_2, NO_x, H_2O, CiC)	Simplified operating cost	Not considered
Becker et al., 2022 [11]	Temporal shift for night contrail avoidance	AGWP (CiC, CO_2)	Not considered	Not considered
Baneshi et al., 2023 [14]	Trajectory optimization	ATR20 (CO_2, NO_x, H_2O, CiC)	Simplified operating cost	Complexity assessment and conflict resolution
Simorgh et al., 2023 [15]	Trajectory optimization	ATR20 (CO_2, NO_x, H_2O, CiC)	Simplified operating cost	Not considered
Gencoglu & Baspinar, 2023 [4]	Routing optimization	ATR20 (CO_2, NO_x, H_2O, CiC)	Direct operating cost	Conflicts and ATC complexity analysis
Zengerling et al., 2023 [10]	Flight level reduction	ATR20 (CO_2, NO_x, H_2O, CiC)	Direct operating cost	Not considered

and operating cost changes are estimated in most of the case studies, e.g. [10], [13], network effects are not covered in a majority of the different analyses. Some studies, e.g. [4], [14], [16], consider air traffic management (ATM) related indicators, for instance, sector load changes or conflicts resulting from optimized trajectories and their possible resolution in air traffic control (ATC). However, an extensive assessment of different trajectory-adaptation measures combining climate mitigation and network effects is still missing.

Hence, the goal of this study is to investigate different climate mitigation approaches by not only looking into the climate effects from different trajectory adaptations but also investigating the resulting impact on the network. For this purpose, we investigate an Intra-European case study with a focus on CiC effects. In this course, we analyze three different adaptation scenarios exploiting geo-temporal variations in climate sensitivity, namely (1) temporal adaptations to flight trajectories defined by take-off time shifts, (2) vertical adaptations to the cruise flight altitudes of trajectories, and (3) an integrated scenario including both temporal and vertical adaptations.

II. METHOD AND DATA

The approach of this paper is displayed in Fig. 2 illustrating our two-step assessment approach. Firstly, we calculate the reference trajectories and their climate effect. On this basis, we introduce suitable trajectory adaptations and estimate climate mitigation potentials for the considered flights. Secondly, we feed both reference case and adapted trajectories to the network assessment to evaluate the feasibility within the European air traffic system.

A. Trajectory assessment

The trajectory modelling is performed with DLR's Trajectory Calculation Module (TCM). Within this tool, different submodules can be utilized. In this study, we integrate the emissions calculation submodule as well as the climate impact assessment with algorithmic climate change functions (aCCFs) as described in the following.

The **flight performance modelling** is performed with the core routine of the TCM [5]. It applies a Total-Energy-Model (TEM) for a forward integration of the aircraft state along the trajectory based on aircraft and engine specific performance data [17]. From the given inputs and configurations regarding route description, take-off date and time, as well as aircraft type, a large set of relevant flight performance parameters are modelled in high resolution for every considered trajectory. This does not only include four-dimensional position data, but also horizontal and vertical speeds, accelerations, lift, drag and thrust values as well as fuel burn. On this basis, also direct operating costs can be estimated in a simplified approach based on aircraft category, total fuel burn, flight time and mission distance [5]. In this study, we apply the TCM in an updated version, which is not only capable of modelling generic flight trajectories, but considers actually flown flight profiles including lateral and vertical position data [10]. Hence, also realistic atmospheric conditions along the actually flown flight missions can be considered.

The **emission flows** along the trajectory can be calculated with fuel-flow correlation methods (FFMs). For CO_2 and H_2O, constant emission factors are applied, while we use DLR's FFM [18] for the calculation of NO_x emission indices in dependence of altitude, temperature, and humidity considering actual atmospheric conditions.

The **climate impact** of each individual trajectory is calculated with aCCFs to account for geo-temporally varying climate effects of non-CO_2 emissions. The definition of aCCFs is based on previously developed climate change functions (CCFs) that have been derived from extensive simulations with the climate chemistry model EMAC for representative weather patterns in summer and winter [19]. Since the application of CCFs in trajectory modelling and optimization is rather complex, aCCFs have been derived in a statistical analysis of CCFs in relation to meteorological parameters, e.g., temperature, pressure, geopotential or outgoing longwave radiation, at the time and location of emissions. They return average temperature response over 20 years (ATR20) resulting from a pulse emission for H_2O, NO_x and CiC as simplified functions

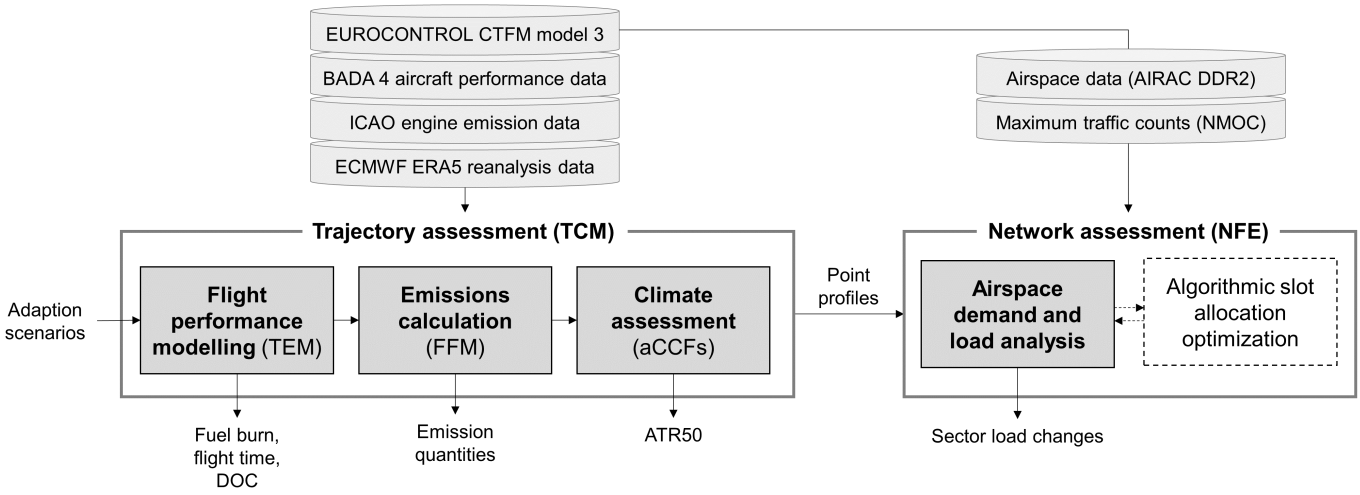

Figure 2. Overview of assessment workflow

in dependence of atmospheric parameters such as temperature, potential vorticity and solar radiation [20], [21]. Hence, precise meteorological information is required for their assessment. A recent advancement of these functions incorporates conversion factors towards climate metrics of other time horizons (50 and 100 years) as well as different emission scenarios [22]. In this study, we apply the most recent update of these functions in Version V1.0A [23]. An exemplary visualization of the merged aCCF aggregated for the climate forcers CO_2, H_2O, NO_x, and CiC is displayed in Fig. 3 indicating areas of high climate sensitivity caused by CiC over Western Europe.

We assess the climate impact in terms of average temperature response over 50 years (ATR50) assuming background emissions in a *business-as-usual* scenario [3]. The evaluation of aCCFs is performed along every considered trajectory based on route information, meteorological parameters and emission flows. Therefore, the climate impact of every mission and the corresponding mitigation potential of different trajectory adaptations can be determined.

B. Network assessment

Trajectory adaptations, for instance by adjusting route, flight profile or time component, possibly lead to changes in demand patterns in the air traffic network and, more specifically, in certain airspaces. In particular, adapting the flight profile changes the airspace profile along the trajectory. This means flying into airspaces (ATC sectors), in which the flight was not initially planned. At the same time, sectors originally being part of the sector profile are no longer flown into, reducing the respective demand. The amount of these demand shifts is evaluated based on the adapted trajectories in the different scenarios.

To this end, we apply the Network Flow Environment (NFE), which is developed at DLR Institute of Air Transport as an evaluation environment to test new and efficient optimization algorithms to solve the air traffic flow management (ATFM) problem, to design and analyze innovative ATFM

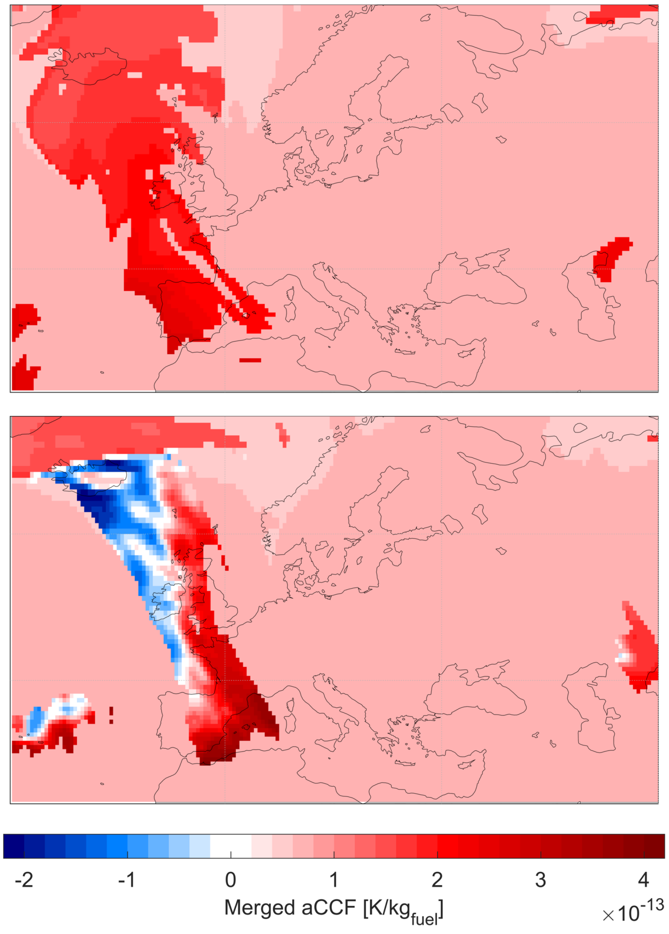

Figure 3. Visualization of merged aCCF regarding ATR20 relative to fuel burn on December 11, 2018 at 00:00z (top) and 12:00z (bottom) at pressure level 225hPa.

measures and to study system reactions of the ATM network in disruptive situations in general [24]. It consists of several functionalities to extract and process different data types for large-scale air traffic flow and capacity management (ATFCM) slot allocation within the European ATM network. Thereby, the slot allocation function is executed by two algorithmic approaches: (1) a heuristic algorithm generating Calculated Take-Off Times (CTOTs), and (2) a binary-integer optimization module, which is able to handle large scale ATFM problems. Delay minimization as the result of balancing network resources with traffic demand represents the computation goal for each time horizon being implemented within a rolling time-horizon computation architecture [25]. However, the focus of this study is the airspace demand and sector load analysis resulting from the different scenarios of trajectory adaptations. An integrated slot optimization can easily be considered in future studies.

C. Study set-up

The reference case of this study is defined as follows: We concentrate on the European airspace for the assessment of network effects due to the special interest in the feasibility of implementing climate-friendly trajectories in a high-density airspace. Consequently, we focus on European flights only and assume no changes to remaining flights in the European network. As the climate effect is significantly influenced by the weather situation, thus varies from day to day and between the seasons of the year, we select one exemplary winter day for our case study. Winter is of special interest due to its higher CiC reduction potential compared to summer [26]. The longer night times in the European regions also lead to longer times where CiC lead to a warming effects only. Given the fact that there is less traffic demand in the network in winter compared to summer, this particularly justifies the choice of a winter day in order to be able to provide the necessary flexibility for spatial and temporal trajectory adjustments. Based on this, future studies will additionally examine high-demand days in summer. December 11, 2018 has been identified as a case study day within the ClimOP project considering its representativity for the winter season in the European region [10].

In accordance with [9], [11], we focus on Intra-European flights with a high climate impact of CiC. Fig. 4 shows the distribution of the aggregated climate impact based on the assessment of all considered trajectories. It indicates that approx. 10.5% of all European flights account for 80% of the climate impact of CiC in this case study and approx. 20% of the flights account the entire contrail-induced climate impact. We find a net-cooling contrail effect for 9.6% of the flights, while along a majority of the trajectories no CiC can be observed (Fig. 3).

To mitigate the climate impact, we consider three different adaptation strategies to reduce the climate impact of the respective flight mission in general and the contrail effect in particular. The considered scenarios are as follows:

- **Temporal adaptation scenario**: The influence of day and night time on the climate impact of contrails is utilized to reduce the warming effect of contrails. Hence, take-off time of individual flight missions is shifted in 60-minute intervals between -180 and +180 minutes from reference take-off time. In case a reduction of the climate impact can be achieved, the new take-off time is utilized to define the adapted trajectory.
- **Vertical adaptation scenario**: Since contrails are typically of a wide lateral and a small vertical extension, this adaptation strategy aims for an avoidance of contrail-forming regions by changing the cruise altitudes. We consider changes to the reference cruise flight level of +2000 and -2000 feet. For each individual mission, trajectory and cruise flight level with the lowest climate impact are selected.
- **Integrated adaptation scenario**: A combination of temporal and vertical adaptation is introduced to investigate the overall climate mitigation potential.

D. Applied data

For the implementation of this study, we apply EUROCONTROL Current Tactical Flight Model (CTFL model 3) trajectory data representing updated flight plans based on surveillance data reflecting route adjustments [27]. Base of aircraft data version 4.2 (BADA4) data is used for the trajectory modelling providing relevant aircraft and flight performance data [17]. For the emissions calculation, we use reference emission indices from ICAO Engine Emission Databank [28]. Atmospheric conditions are considered according to European Centre for Medium-Range Weather Forecast (ECMWF) ERA5 reanalysis data provided in 3 hours temporal and 0.25° lateral resolution [29]. Moreover, airspace and network environment data are used and matched according to the considered AIRAC cycle 13-2018. Thus, the

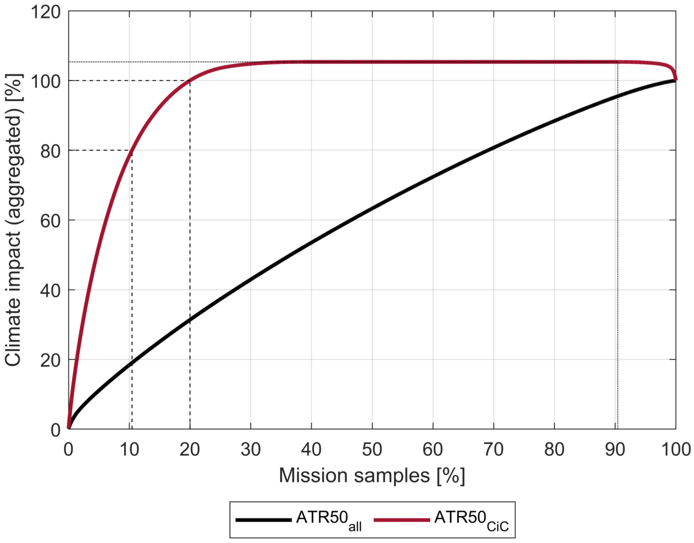

Figure 4. Accumulated climate impact of considered flight trajectories. Mission samples are sorted by CiC climate impact in descending order.

ATM network is represented by air route, waypoint, airspace and airport data.

III. CLIMATE MITIGATION POTENTIAL BY TRAJECTORY ADAPTATION

The resulting climate mitigation potentials are presented for the different adaptation scenarios in the following before we look into network effects in Chapter IV.

A. *Individual flight case study*

To demonstrate the approach of the study, we firstly analyze effects on an exemplary mission in an individual flight case study. A flight from Vitoria, Spain (LEVT) to Liège, Belgium (EBLG) with a common narrow-body aircraft starting at 22:18 UTC on Dec 11, 2018, requires approx. 3.6t of fuel and takes 1:30h for a flight distance of 1,120 km. We observe contrails in the second half of the flight mission at a flight altitude of 32,000 feet with a significant CiC warming effect contributing to about one third of the total ATR50 of this trajectory (Fig. 5).

The considered adaptation strategies change the climate impact in different ways. A downward shift of the cruise flight level as well as earlier take-off times do not mitigate the climate effect of CiC. For instance, a vertical shift of the cruise flight level by 2000ft in this case increases both fuel consumption (+ 2.7%) and climate impact from CO_2 as well as non-CO_2 species (+16.0% in total).

By contrast, the upward shift of trajectories shows significant mitigation potentials (-6.6% in ATR50) mainly caused by a reduction in CiC effects (-13.0%), while flight time and fuel burn change marginally (Fig. 5). Even higher mitigation potentials can be achieved by shifting the take-off time. When shifting the take-off time by 3 hours, the highest mitigation potential of approx. 13% can be achieved. This is due to a reduction in CiC climate effects of 43% as the formed contrails do not only appear during night but also last until sunrise leading to smaller warming effects in this example.

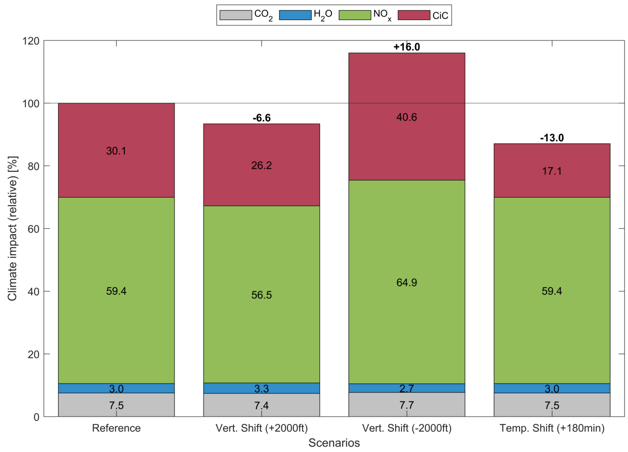

Figure 5. Climate impact and mitigation potential for different scenarios on exemplary route. Numbers give contribution relative to the reference case.

TABLE II. ADAPTATION SCENARIOS AND CHANGES IN CLIMATE IMPACT

	Temporal adaptation	Vertical adaptation	Integrated adaptation
Adapted flights	388	1395	1470
Adapted flights [%]	1.4	5.0	5.3
Change in ATR50 for adapted flights [%]	-7.1	-9.8	-9.9
Change in ATR50 of CiC for adapted flights [%]	-48.5	-84.2	-87.1
Change in ATR50 for entire scenario [%]	-0.1	-1.7	-1.8
Change in ATR50 of CiC for entire scenario [%]	-13.0	-57.6	-61.7

B. *Temporal adaptation scenario*

Analyzing the scenario of temporal adaptation, we find that approx. 400 flights can benefit from a shift of take-off times to mitigate the climate impact. Hence, 1.5% of all missions in the European airspace on that day are changed in this scenario. Looking into the considered high-impact missions only, the 400 missions represent a share of 19.9%. We observe 56% of the adapted missions with earlier and 44% with later take-off times.

In course of the temporal adaptation, on average half of the contrail-induced climate impact (48.5%) can be mitigated for the adapted flight missions leading to a merged mitigation potential of approx. 7% (Table II). Looking at all investigated Intra-European flights, the contrail reduction potential of 13% is significant.

However, due to the high impact of other emission species for the considered weather situation (Fig. 3) and the small share of adapted flights in this scenario, we observe a very limited overall mitigation potential (0.1%). Insignificant changes to fuel burn, flight time, operating cost and other climate effects are advantages of this scenario. Nevertheless, required changes to the air transport system, e.g. regarding the airlines rotation planning, need to be considered for a realistic implementation analysis.

C. *Vertical adaptation scenario*

By contrast, a larger share of flights is adapted in the vertical adaptation scenario. Approx. 5% of all flights in the European airspace are affected and a majority of the flights with the highest CiC impact are changed. Hence, we observe higher mitigation potentials of 84% on average for CiC climate effects and 10% for the merged ATR50 of the adapted flights (Table II). This leads to an overall mitigation potential of 58% for CiC and almost 2% for the merged climate effects of the entire sample of considered flights. Fig. 6 shows the adjusted trajectories indicating that those trajectories are adjusted which cross the areas of high climate sensitivity, respectively areas of contrail formation (Fig. 3).

About 60% of the adapted flights see a vertical downward shift. This can be explained by the fact, that the climate effect from other non-CO_2 species also depends on the emission altitude, so that a reduction in flight altitudes also reduces climate effects from H_2O and NO_x. In comparison to the

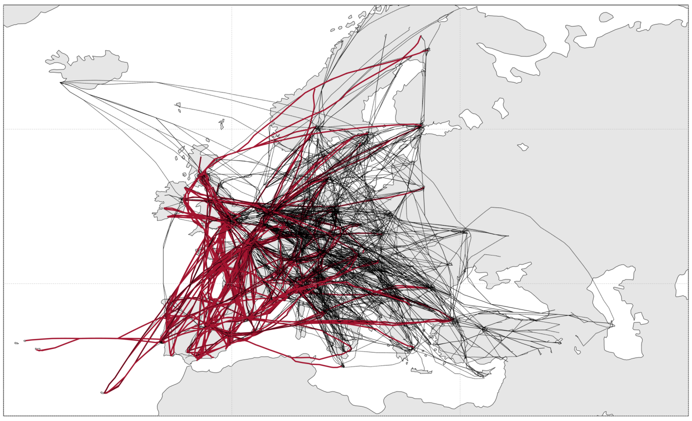

Figure 6. Trajectories in vertical adaptation scenario at 12:00z. Red trajectories indicate vertical adjustments, black trajectories remained unchanged.

temporal adaptation scenario, fuel burn, flight time and cost change more markedly due to changes in fuel efficiencies with changed altitudes.

D. *Integrated scenario*

The integrated scenario combines temporal and vertical trajectory adaptations depending on the highest mitigation potential. Therefore, 1470 trajectories are adapted increasing the number of changed flights in the vertical scenario. 172 of the flights (11.7%) are temporally adjusted, while 44% benefit from a lower cruise flight level. CiC climate effects are reduced by 87% for the adapted flights leading to an overall mitigation potential of 1.8% (Table II).

IV. NETWORK ASSESSMENT

As different kinds of data types are used, the merging process of traffic and environmental data is important in terms of an assignment of flights to airspace sector in order to generate traffic load matrices for all sectors over time for the reference and adaptation scenario. Due to the deterministic character of the 4D trajectories, entry times for each airspace as part of the individual sector profile can be determined. Time slots with a duration of 15 minutes have been applied. With regard to available network resources, nominal maximum values of allowable entry rates into airspaces are present within the NFE. Therefore, a computation of ratios between entry counts and defined maximum nominal capacities for each sector as a function of time is possible for different traffic scenarios. The network analysis was based on the metric of normalized difference in entry counts in relation to the reference demand capacity ratio as a mean value for all scenario time slots.

Fig. 7 shows changes in airspace utilization resulting from the vertical adaptation for different flight levels. As for approx. two thirds of the vertically adapted trajectories the cruise flight level was shifted down compared to the reference trajectories (Chapter III-C), this affects the network in terms of increasing entry rates into lower sectors, as indicated for a reference FL350 (Fig. 7, top). Especially the sectors over western France and the Bay of Biscay show significant increases in entry rates consistent with the location of areas with high climate sensitivity, i.e. where contrails form (Fig. 3). Higher sectors, e.g. with a reference FL370 (Fig. 7, bottom) show decreases in entry rates and basically match the observation of traffic shift within staggered sectors. The fact, that the increase in entry rates in the lower sectors does not completely match the decrease in entry rates in the upper sectors is due to the vertically staggered airspace structure as well as the evaluation across all time slots representing the whole traffic scenario.

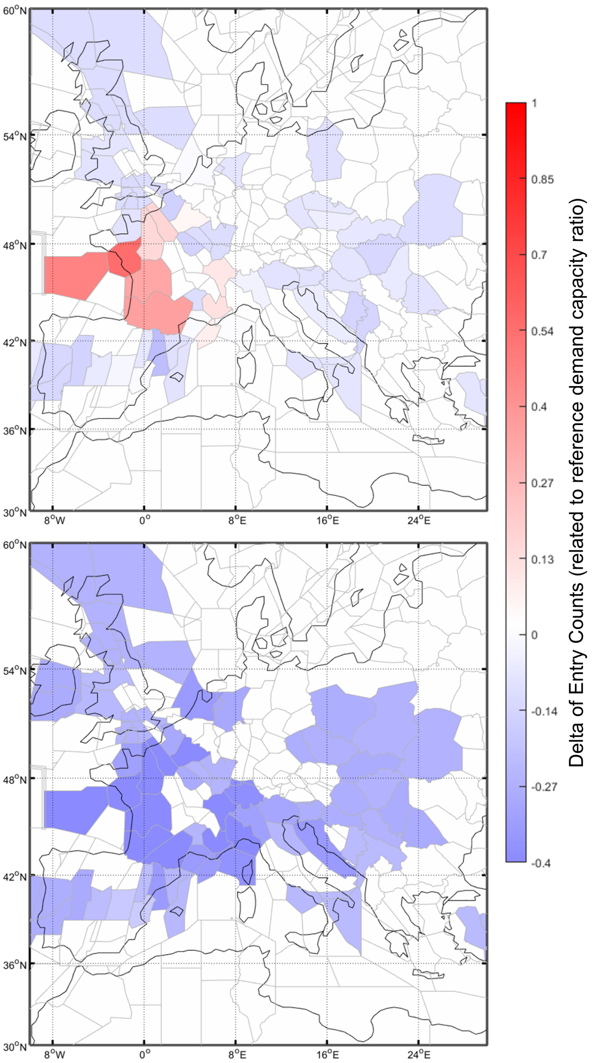

Figure 7. Changes in airspace utilization indicated by the difference in entry counts in the vertical adaptation scenario for FL350 (top) and FL370 (bottom)

Fig. 8 shows the results of a hotspot analysis for the vertical and temporal adaptation scenarios at a time of 06:00z. This point in time represents comparably high demand in the respective airspaces. Different demand rates are shown by proportional traffic loads, interpreted by a color coding of 4 different utilization levels. Sectors over northern Spain, Ireland and Sweden indicate high demand of over 100%, whereas those indications do not allow for an interpretation of constant overload. Differences between the vertical and temporal adaptation scenario are marginal, whereas a slightly

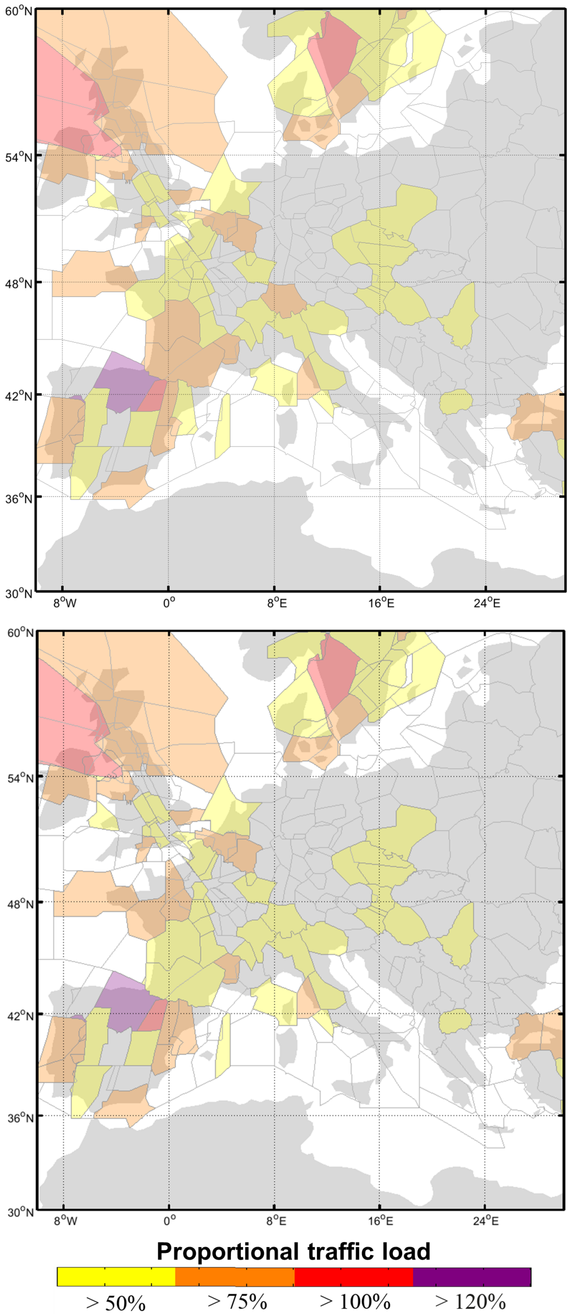

Figure 8. Hotspot analysis for the vertical (top) and temporal adaptation scenario (bottom) at 06:00z.

higher demand is indicated for the vertical adaptation scenario over France. Strong differences in sector demand rates are certainly possible with variable departure times, but do not show a major network effect at this point. Furthermore, the combination of both earlier or later individual missions within identical traffic flows allows for the possibility of balanced demand rates (Chapter III-B).

V. DISCUSSION

In consistence with the state of literature, our results show high mitigation potentials of trajectory adaptations to avoid contrail-forming regions (Table I). We confirm the results from [11] that vertical shifts provide higher mitigation potentials compared to temporal adjustments. The approach of focusing on high impact flights according to [9] is promising especially when investigating influences on the air transport system. For the first time, we combine these results from climate impact assessment of trajectory adaptations with an investigation of network effects, which become visible, particularly regarding vertical adaptations of the cruise flight level. The approach of focusing on high impact flights though restricts network effects to areas of high climate sensitivity and limits the impact on the entire European network in this case study.

Nevertheless, short-comings of the method as well as related uncertainties and inaccuracies need to be considered when interpreting the results of the presented case studies. On the one hand, the climate effects from non-CO_2 species are still considered very uncertain and estimated to be eight times higher compared to CO_2 effects [1]. While the formation of contrails can sufficiently be described, the associated warming and cooling effects cannot be determined accurately yet [1], [21]. On the other hand, simplifications in the trajectory calculation and modelling of network effects imply inaccuracies, for instance regarding aircraft performance, weather and deterministic trajectory representations in the network context.

Moreover, the presented case study has been evaluated for a restricted study scope. To extend scientific significance of the results, a larger set of days and weather situations as well as more comprehensive flight samples are required. Higher air traffic density in summer is expected to affect results. Nevertheless, the selected winter day indicates the influence of avoiding warming contrail forming regions on the air traffic system. Furthermore, increasing traffic rates and higher complexities in lower airspaces need to be considered in detail in the future. Moreover, further mitigation approaches (e.g. the combination with alternative fuels or trajectory optimization) can extend the comparison as well as the consideration of further stakeholder effects regarding airlines or passengers. In this context, operational implementability needs to be further investigated considering airline network effects from climate-optimized flights [12], [30] as well as precision of weather forecast data to enable their consideration in climate-optimized trajectory planning.

VI. CONCLUSION

This study sets the basis for an analysis of climate mitigation potentials from trajectory-related approaches considering influences on the European air traffic network. We demonstrate our approach integrating trajectory optimization and network assessment to investigate the feasibility of trajectory-related climate mitigation measures. The results of our European case study for a selected winter day show high mitigation potentials of contrail-induced climate effects for a vertical adaptation strategy. Changes in the network, hotspots and capacity changes, are concentrated in areas with a high contrail climate impact. Network optimization, e.g. by prioritization of trajectories with a low climate impact, and the design of innovative air traffic flow and capacity management measures expands the scope of a climate sensitive air transportation system and requires further investigation following this study.

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