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Considerations for multi-criteria Route Design on Different Atmospheric Scales

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More than ever, air traffic today needs to adapt to atmospheric conditions to be able to operationally mitigate the effects of air traffic emissions on one hand, and to ensure safe operations on the other hand. This study provides considerations on how to integrate atmospheric disruptive events and climatological objectives of different algorithmic scales in the context of trajectory design, for which the mission level is in focus. We found, that route efficiency depends on the scale and the frequency of atmospheric impacts along the route. The ground distance of the optimized routes for the considered O-D pairs and the scenario design increases by up to about 6% when both smaller-scale impact types, convection and climate sensitive areas, are considered.

Keywords: Route Design, Convection, Climate Costs, Optimization

1. Introduction

Trajectory design is driven by a multitude of impact factors, each representing individual needs related to flight safety, economic efficiency and climatological impact reduction. Thereby, it is challenging to declare a specific flight trajectory an optimal trajectory without providing to which relation optimality is given. Especially on the mission level, the discrepancy between tactical design goals related to safety-relevant weather patterns, like e.g. convective weather, and more strategic climatological goals, i.e. by reducing the impact of non-CO2 emissions, is challenging. The fact that there is an economic dimension in both types of trajectory design areas complicates the need to find optimally designed trajectories. What is needed is a methodology to integrate different types of atmospheric data to come up with a route design, which integrates these inputs of different scales including wind. This study intends to discuss different atmospheric impact types on trajectory route design, i.e. convection as a small-scale event, and wind as well as climatological sensitive areas as mid-size and larger-scale events and its possible impact on lateral efficiency. In addition to statistical evaluations related to concrete O-D-pairs, an integrability into a multi-criteria trajectory optimization will also be discussed in terms of cost scaling for different impact types.

2. Atmospheric Impact Types

2.1 Convection

Convective weather is characterized by safety-relevant properties, which can have a substantial impact on flight safety. Those are precipitation including hail, strong vertical and lateral air movements, icing, and general turbulence [3]. It is triggered by a deep conditionally warm stable atmospheric layer existing from ground upwards, in which the temperature is higher than in the surrounding air establishing a continuous upward air flow. This leads to cumulus thunderstorm cells, which can have a strong manifestation of the mentioned characteristics. Possible effects on aircraft during cruise and landing are different. During cruise, strong air upflows may lead to strong turbulence above the convective systems, which may reach upper airspaces due to higher warming effects justified by atmospheric warming. Wind effects in the vicinity of convective systems near the ground may compromise safety of departing and landing aircraft. These up- und downdrafts mainly occur on the front side of a thunderstorm.

Thunderstorms usually develop as frontal thunderstorms or in the form of single embedded cells. Figure 1 provides typical thunderstorm configurations in Central Europe, whose lateral extension is manageable on a global scale. In particular, the extent of embedded cells is usually not greater than a few hundred meters, which means that they have a small influence on the lateral trajectory design, especially in case of long-haul flights.

The convective model data used for this study comes from Cb-Global, which is a technical system developed for the detection, tracking and nowcasting of convective cells based on geostationary meteorological satellite data [8],[9]. It processes data from several meteorological satellites like METEOSAT and therefore covers the globe with a spatial resolution of up to 500m and with an update rate of up to 5 minutes depending on the satellite instrument. Several development stages of convection can be identified by the use of data from one high resolution visual, two infra-red, and one water vapor channel. The applicability and its qualification for flight planning and trajectory design purposes has been proven in several studies [3],[7].

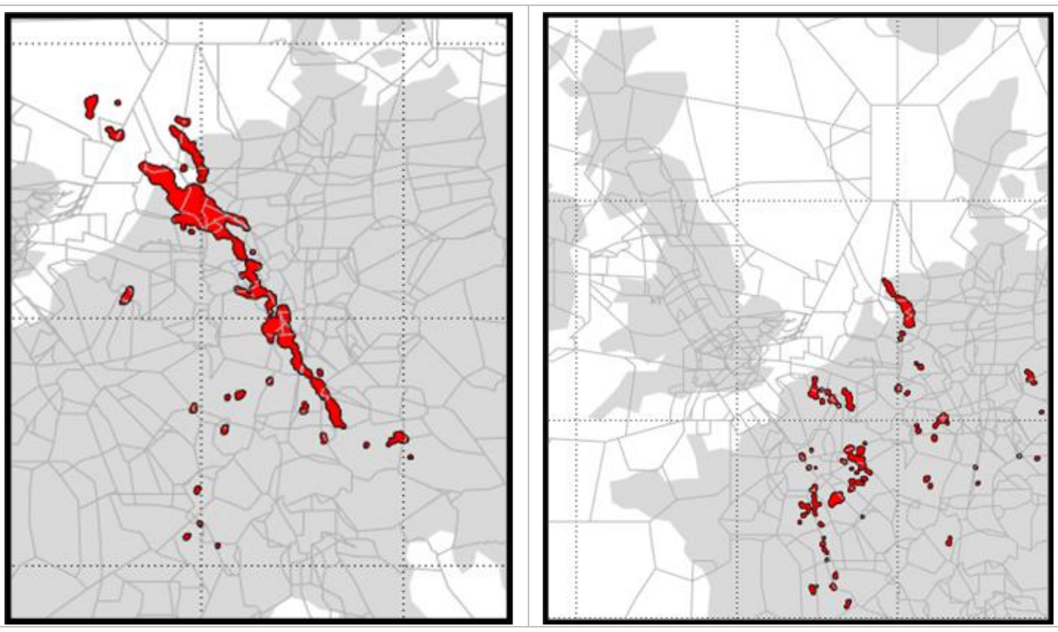

Figure 1 - Convective cell structures (data source: Radar Tracking and Monitoring, Rad-TRAM [4]) on an ATC sector network of all flight levels, red cells with an inside radar reflectivity of >37dbZ, left: frontal cell structure, right: embedded cell structure

2.2 Wind

The understanding and the ability of the prediction of upper-tropospheric wind systems have a significant impact on the flight planning process and on the lateral route in general [1]. Especially the east-west orientated Jet Stream within the North-Atlantic airspace represents one of those large-scale wind patterns, which have a major impact on highly-frequented air route structures - the North-Atlantic Track System (NATS). The polar Jet Stream is an eastbound wind and runs between 40 to 60 degrees latitude in about 10km altitude with wind speeds up to 500 kilometers per hour, c.f. **Figure *2***. It is a large-scale atmospheric structure with a profound impact on operating cost and therefore on trajectory design. In the eastbound (tailwind) case, engine thrust is reduced, since tailwinds add to the aircraft speed and thus increase the ground speed, which consequently shortens flight time [2]. Considering the westbound case, wind increases effective air distance. Thus, routes mitigating areas of strong headwind with high re-routing factors may still be efficient.

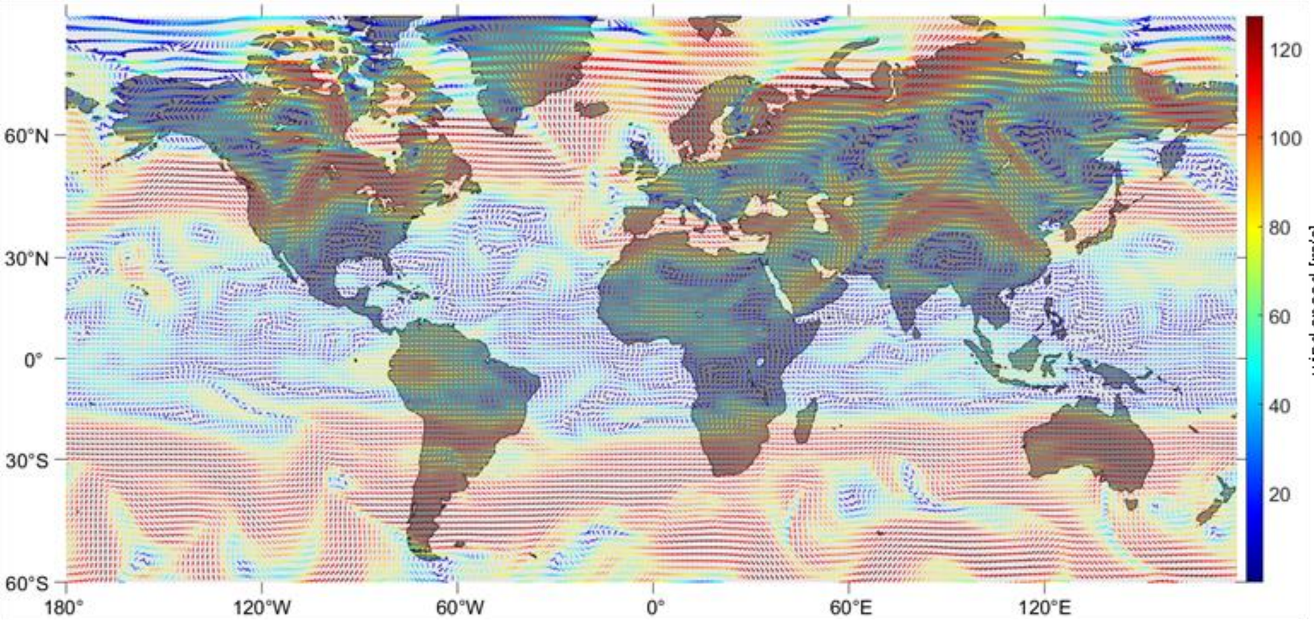

Figure 2 - Representative Global Wind Speed and direction on FL 350

The focus of large-scale wind optimization is clearly on the cruise segment of the flight, which has the greatest impact on flight efficiency due to the highest share of fuel consumption. However, in the last decade, changes of the atmospheric Jet Stream could be observed. Instead of fast and almost parallel wind patterns, wind speeds decrease with the consequence, that the jet stream is less fast with a higher directional variability over the northern hemisphere, which may be assigned to climate change. In any case, the integration of highly dynamic wind patterns into trajectory design needs to be conducted, but is dependent also on the other atmospheric parameters.

2.3 Climate Sensitive Regions

Air traffic is not only responsible for CO_2 emissions but also for non-CO_2 effects due to the emission of water vapor and nitrogen oxides as well as the formation of contrails. The latter have an impact on climate, since they change the concentration of radiative forcing agents in the atmosphere. As elaborated by Lührs et al. [5], climate change functions (CCFs) measuring the climate impact of CO_2, NO_x, and water vapor as well as contrails, have been developed, which provide the possibility to quantify climatological impact based on emission location and time. Moreover, algorithmic climate change functions (aCCFs) [6] allow for fast and efficient simulation of climate impact based on the given weather situation. It is therefore possible to identify those regions and airspaces where emissions have a higher impact on climate change in order to avoid them in flight planning. **Figure *3*** provides algorithmic climate change functions for NOx and contrails on a winter day on flight level 390 within the European airspace. In terms of lateral expansion, contrail sensitive regions in this example are not more expansive than a pronounced convective front.

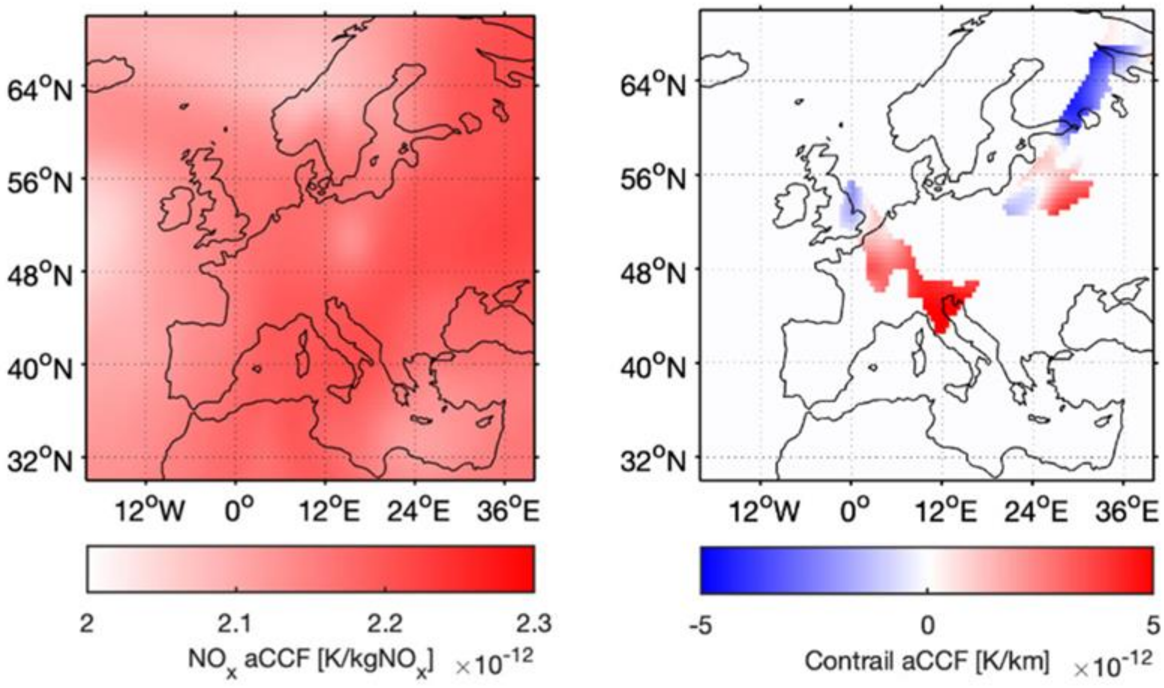

Figure 3 - Algorithmic climate change functions for NO_x (left) and contrails (right) as a function of latitude and longitude on FL390.

3. Considerations for Route Design

Given the atmospheric impact types described in Chapter 2, different possible types to represent these conditions may lead to different mitigation, or diversion strategies. Therefore, this chapter initially provides a description of the trajectory optimization framework and the application of the atmospheric data types applied to generate a most optimal multi-criteria route design. Moreover, the impact scenarios and the considered O-D-pairs are described and evaluated in order to find the best data integration and application strategy for a successful and stable execution of route optimizations.

3.1 Optimization Framework

The trajectory optimization framework presented in this paper builds upon the Dymos library for optimal control of dynamic multidisciplinary systems [10], which is based on OpenMDAO [11]. We use this library to model route optimization as an optimal control problem which seeks to find a feasible trajectory by minimizing a given cost function. Depending on the optimization target, this cost function may only represent the flight time, or include additional factors. In order to avoid convective areas, a penalty term can be added which effectively prevents routes being partly located within convective areas. Similarly, climate change functions can be added to the cost function, incentivizing the solver to avoid climate sensitive areas.

The optimal control approach we use in Dymos needs a given initial trajectory, and tries to find a locally optimal solution. It may thus get stuck in a solution which is locally optimal, but inferior to a globally optimal solution. We therefore pre-compute solutions with a Θ*-algorithm [11]. Here, the costs of an edge, which connects two points, equals the costs of the great circle between these points, which are presented to the optimal control solver. Therefore, these pre-computed solutions are representing initial routes. **Figure *4*** shows the difference between solutions computed in these ways: It can be seen that, if the solver starts from the great circle, the trajectory is fixed by the gradient of the cost function. On the right-hand side, the initial solution was chosen depending on the cost function at hand, and could therefore be placed optimally, resulting in better solutions from the optimal control solver.

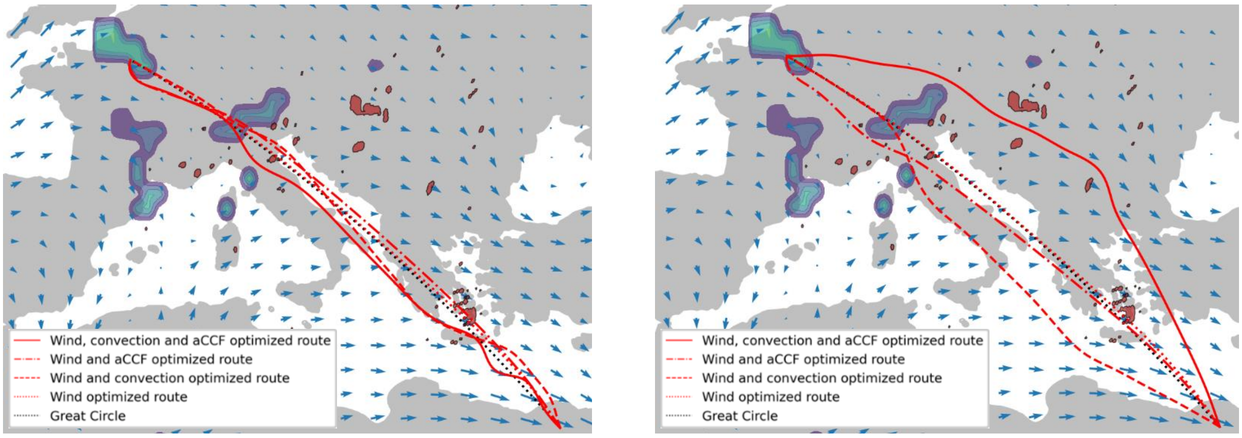

Figure 4 - Solution when Optimal Control is initialized with the great circle route (left), and from an initial discrete solution computed with Θ* (right). It is obvious, that the optimized route at the left side is penalizing climate sensitive areas, whereas the optimized route at the right side can be considered as conflict free on the cost of a higher re-routing factor.

The overall design of the optimization process is shown in ***Figure 5***.

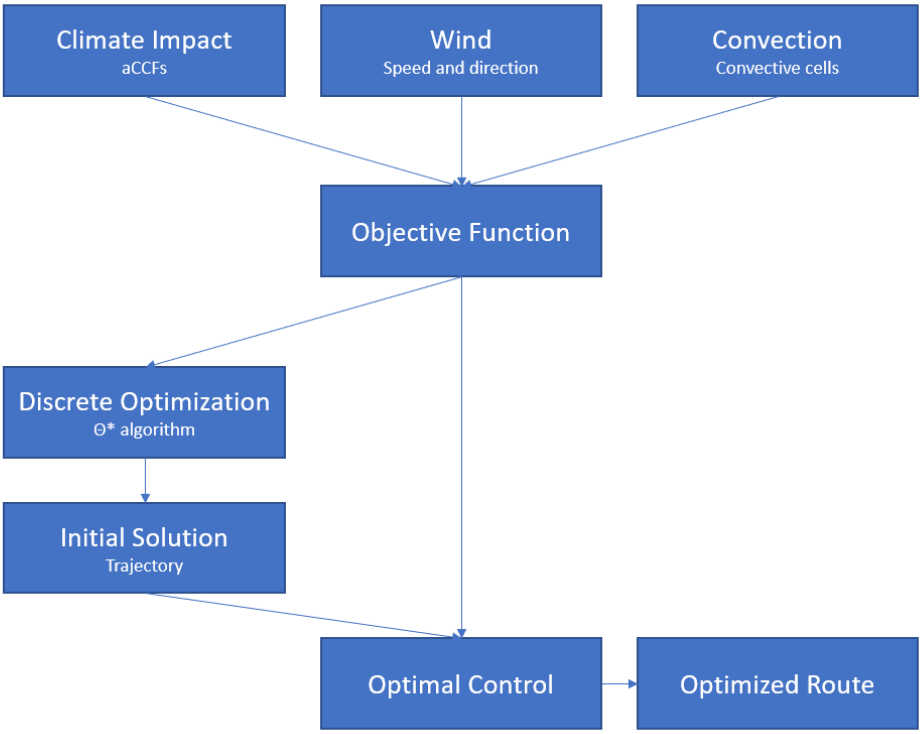

Figure 5 - Model Flowchart for multi-criteria route optimization

3.2 Scenarios and Data Application

In this study, we analyze the effect of applying different design criteria to the route optimization process. From an optimization process perspective, all optimization criteria are reduced to their impact on the objective function. Thus, they are reflected in topological properties of the objective function and in this context are more important than the detailed physical background of the atmospheric impacting phenomena. Herein lies the need in the context of flight planning to make complex influencing factors usable for route design in such a way that they can be clearly interpreted for each route segment. As can be seen in figure 2, the wind forms large-scale structures at cruise altitude having different parametric impact on the cost function as for convective cells being of smaller scales but have to be avoided in any case. In order to move the trajectory away from convective weather, a penalty function is used which incentivizes the optimizer to avoid the respective area. Here, we used a sigmoid-shaped function for penalty cost behavior. Penalty costs are at their maximum inside the convective cell, and drop to zero outside. Still, there exists a gradient, which is important for the optimal control solver to be able to design routes which avoid these zones.

Climate impact, which is reflected in the aCCFs, consists of several individual factors, e.g. the impact of NO_x and contrail formation (c.f. Figure 3). While atmospheric cost structures due to NO_x emissions are of larger scale, contrails form smaller-scale areas dependent on moisture, temperature, pressure fields and other aircraft-related variables. **Figure *6*** shows the structure of the values of the analytic climate cost function and the convective cell polygons on the given wind field.

The objective function used throughout this paper is given by the weighted sum of flight time, climate impact and the penalty for getting too close to convective cells:

$$objective = t_f - t_0 + c_1 \int_{t=t_0}^{t_f} accf\big(\lambda(t), \psi(t)\big) + c_2 \int_{t=t_0}^{t_f} convection\big(\lambda(t), \psi(t)\big) \qquad (1)$$

Here, $\lambda(t)$ represents the longitude at time t, and $\psi(t)$ is the latitude at time t. The starting time is denoted t_0, and the time at which the target is reached is denoted t_f.The climate cost function yields the temperature response in Kelvin per second. Thus, as the unit of our objective function is $[objective] = s$, the unit of c_1 is $[c_1] = \frac{s}{K}$. The penalty function for convective cells is dimensionless, thus c_2 is dimensionless, too. The value of c_1 and c_2 can be used to shift the weight between the individual terms climate impact, the proximity to convection zones, and the minimization of the overall flight time. From variations of these parameters, a pareto front can be computed. Within this study, an initial integration of large- and small-scale impact factors is in focus, considering the integration into the solver. Thus, $c_1 \in \{0, 10^{12}\frac{s}{K}\}$ is used for either representing or neglecting climate impact. Similarly, a consideration of convective cells is conducted by setting c_2 to 0 or 1. Furthermore, for the purpose of this study, it is not of uttermost relevance that the different atmospheric data types stem from a consistent scenario, since we are focusing on static scenarios in order to be able to shape the cost function for a multi-criteria optimization.

We used aCCF values computed for December 18th, 2015, 12:00 UTC. The application of aCCFs is subject to assumptions without qualitatively affecting statements about its application in a route optimizer. In this sense, to identify climate sensitive regions, a true air speed of aircraft of 250m/s during cruise, a cruise altitude of 11.000m, a fuel flow of 0.6kg/s at cruise altitude and an EINOx of 0,013 $kgNO_x$/kgFuel is assumed. Wind data and convective cells represent the situation of May 13th, 2010. Furthermore, we computed routes based on a static situation. The integration of forecasts with an increasing level of uncertainty is not part of this paper.

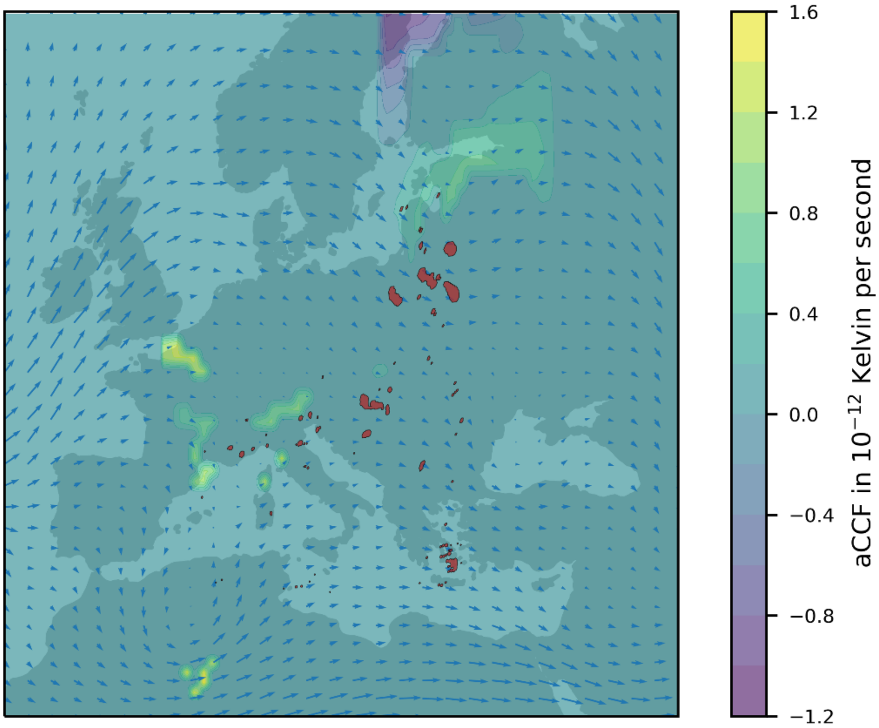

Figure 6 - Analytic Climate Cost Function in the European airspace and convective cell polygons (red), in which radar reflectivity is greater 37dBZ. The lateral scaling of these impact types is comparatibly similar in this exemplary atmospheric scenario.

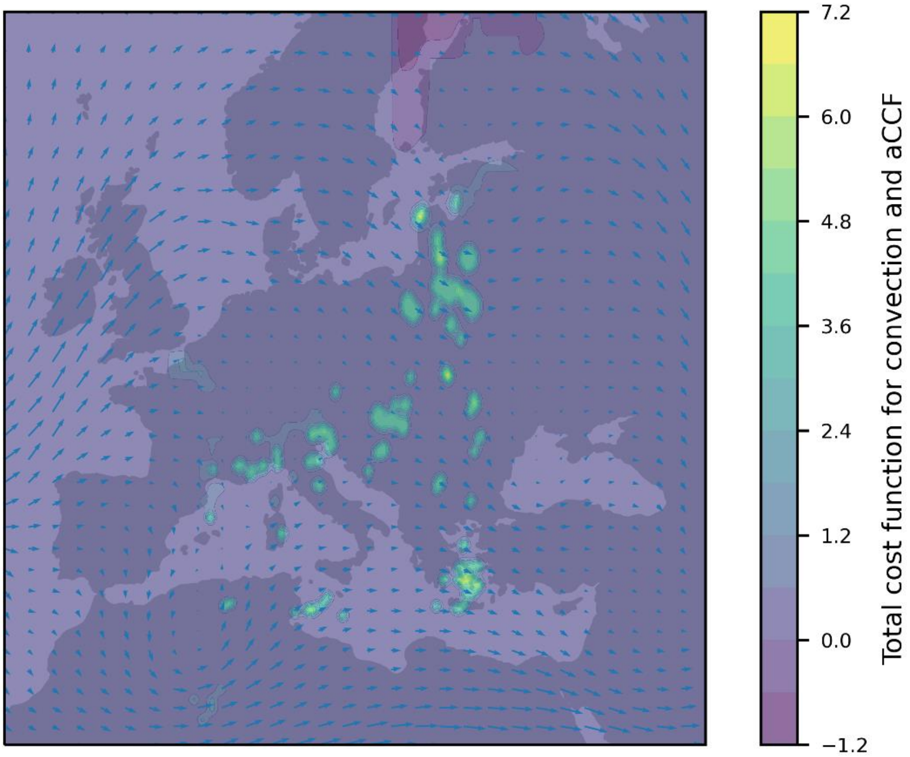

Figure 7 - Total cost function for convection and analytic cost functions in the European airspace used in the optimization. This representation reflects the different cost scales / scaling factors of no-fly-zones for the cost function, compared to the climate cost function.

In comparison to Figure 6, Figure 7 provides a visual representation of the comprehensive cost-function like being used for the route optimization. Firstly, the nominal costs are higher due to the high convective penalization costs representing convective cells as “no-fly-zones”. Secondly, due to the convective cost function shape in order to represent cost gradients around the cells, the cells laterally grow larger, and partly being merged. This can make sense for cell clusters with a high number of very small cells. The optimization usually treats such cell clusters as a continuous object, especially when the initial solution already avoids these cell clusters with a larger detour.

3.3 Evaluation

In order to assess the impact of different cost functions according to different types of impact scales, the designed optimization scenarios include four different cost functions: i.) routes were optimized for minimum travel time under the consideration of wind, ii.) aCCFs were added to the cost function so that the optimizer tried to find a route which minimizes both travel time and climate impact, iii.) convective area were considered resulting in routes which minimize travel time while avoiding convection, and iv.) routes were computed which consider both aCCFs and convection while also keeping travel time as low as possible. For these four types of cost functions, optimized routes for four O-D-pairs have been compared: Athens (ATH) - Helsinki (HEL) (a), Cairo (CAI) - Paris (CDG) (b), Madrid (MAD) - Tel Aviv (TLV) (c) and Madrid (MAD) - Vienna (VIE) (d). These O-D-pairs have been selected based on the designed impact scenario. **Figure *8*** provides optimized routes for all O-D-pairs with different and multiple combinations of cost functions.

3.3.1 Differences between Routes

The great circle between the Athens and Helsinki (a) crosses a larger area of high aCCF’s and multiple convective weather cells with southeast-bound wind (c.f. **Figure *8***a). The wind optimized route is being pushed east, especially in the northern part. Even though ground distance is longer compared to the great circle, the air-distance is being reduced by taking advantage of the wind. When optimizing for wind and aCCF, the route is being pushed westwards of the great circle route, trying to avoid the area southeast of Helsinki with higher climate costs. It is also evident that the wind and aCCF optimized route passes directly through a cluster of convective cells. When optimizing for wind and convection, the route is being pushed further to the east to most effectively minimize the distances being flown in convection and climate sensitive areas. Both, large-scale cost functions for wind and the medium- and small-scale cost functions (convection and climate sensitive areas) significantly influence route design, whereas wind impacts the whole route from departure to destination and convection and climate sensitive areas have a major impact on the affected route segments.

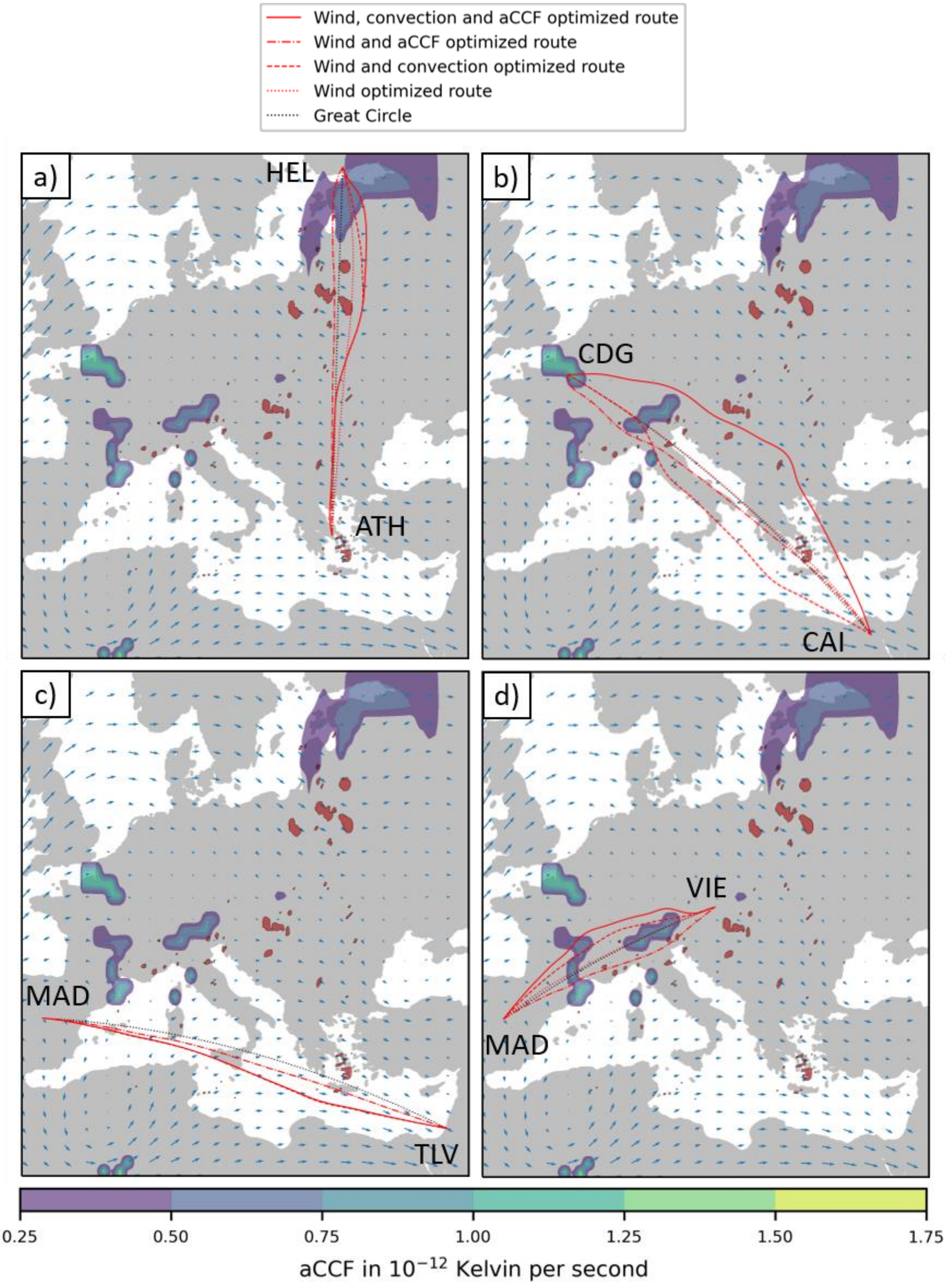

Figure 8 - Optimized routes for four different Origin-Destination pairs and multiple combinations of cost functions. Red polygons depict convective weather cells.

Regarding the route design between Cairo and Paris (b), it is noticeable that the wind-optimized route strongly resembles the great circle, penalizing areas of high climate sensitivity and convective cells. The wind and convection optimized route is further south and bypasses small scale convection with a large lateral buffer. The wind and climate optimized route is also further south of the great circle in the French airspace and avoids areas of high aCCF values. When all three cost functions are combined, the route is much further northeast of the great circle, resulting in a higher ground distance. The sum of medium scale aCCF areas and small scale convection is interpreted as large scale area which to be bypassed as a whole.

The great circle route design between Madrid and Tel Aviv (c) does not penalize areas of high climate sensitivity or convective activity. The wind optimized route is further south to take advantage of the stronger east-bound winds, but therefore crosses convective cells. The aCCF cost function does not appear to have a significant impact on the route design in the case examined. It can also be seen that convection-optimized routes circumvent convective cells with a larger buffer. Thus, in that case, local small-scale convection impacts the overall route design since other impact types do not represent strong restrictions.

Madrid and Vienna (d) has the shortest distance of the selected cases with a great circle passing through two major areas of high climate sensitivity. Several small-scale convection cells are located south of the great circle route. The wind optimized route strongly resembles the great circle, the aCCF optimized route is south of the great circle and crosses several small-scale convective cells. When considering the convection cells for optimization, the routes are placed further north. It is obvious, that also in this case of a relatively short route, local convection has an impact on the design of the whole route. All four routes cross an area of highly climate sensitive regions over France, since alternate routes would have large detours. An interesting finding is that the route optimized for all three cost functions is even farther north with a less efficient route design than the route optimized only for wind and convection. This is because in the case of a combination of aCCF and convection cost types, route length is no longer as significant during optimization, depending on the individual cost level.

In summary, it can be stated for the selected scenario, that for the optimized route designs, convection and aCCFs dominate over wind. Routes optimized for convection have large lateral distance to the actual convective cells. This is due to the high scaled cost function for convection, which leads to higher buffer zones. In the case of cost functions for convection being scaled down, the optimized routes often pass through the convection cells, since the cost terms of wind, time and aCCF dominate. If the boundary function for determining the soft edges of the convection cells is too steep, the optimizer does not converge.

3.3.2 Impact of Optimization Parameters on ATS Efficiency

Next, we discuss the ATS efficiency of the computed routes. An overview over the values is given in **Table *1***.

Table 1 - ATS-efficiency for optimized routes for cost-functions and considered OD-pairs.

ATS-efficiency	wind	wind convection	wind aCCF	wind convection aCCF
Athen - Helsinki	1.0039	1.0159	1.0033	1.0242
Cairo - Paris	1.0007	1.0311	1.0130	1.0572
Madrid - Tel Aviv	1.0015	1.0096	1.0015	1.0090
Madrid - Vienna	1.0005	1.0129	1.0151	1.0404

For the routes between Athens and Helsinki, the wind and climate optimized route is more efficient than the wind only optimized route. This is due to the fact that ATS efficiency is based on ground distance and does not consider wind. The wind optimized route is 97 seconds faster than the one optimized for wind and aCCF (10.244 seconds compare to 10.341 seconds). The route optimized according to wind and convection is about 1.2% longer than the wind optimized route. Finally, the route with all cost terms considered (wind + convection + aCCFs) is about 2% longer than the wind optimized route.

The wind optimized route from Cairo to Paris has an ATS efficiency close to 1.0 and is thus very similar to the great circle. This is beside other reasons related to weak wind velocities over France. If convection is additionally considered, the route is about 3% longer. With climate costs considered, it comes to about 1.2% route extension compared to the wind optimized route. If all cost functions are considered, the route is about 5.7% longer. This is consistent with the findings from Chap. 3.6, where a large lateral offset to the great circle was shown due to the combination of several small-scale convection cells and medium-scale climate sensitive regions near to the great circle.

For the Madrid and Tel Aviv O-D-pair, the wind-only and the wind-aCCF optimized routes have the same ATS efficiency. This reinforces the observation, that in the shown setup, climate costs do not have a significant impact on route design. Considering all cost functions, the route is about 0.9% longer than the wind optimized route. It is remarkable that the wind and convection optimized route is longer than the route optimized according to all cost functions. The aCCF cost function seems to have a gradient (not visible in the figure), which pushes the route closer to the great circle.

As seen for the route between Cairo and Paris, the wind optimized route between Madrid and Vienna has an ATS efficiency close to 1.0 and is thus very similar to the great circle. Compared to the wind optimized route, the route is about 1.3% longer when convection is considered, and about 1.5% longer when aCCF is considered. If all cost functions are considered, the route is extended by approx. 4%.

In summary, the cost terms representing convection and aCCF have a stronger influence on the route design than wind when considering ATS efficiency. The ground distance of the optimized routes for the considered O-D pairs increases by 0.9%-5.7% when convection and aCCFs are considered. Larger extensions of ground distance occur primarily when the great circle crosses multiple small-scale convection cells as well as medium-scale climate sensitive regions.

3.3.3 Impact of Optimization Parameters on Variations of the Heading

Next, we consider the variations of the heading in the different routes. Respective figures are given in **Table *2***. The rationale behind this is that it is challenging to tactically integrate and manage trajectories with constantly varying heading from the ATC perspective, i.e. separation management, implying a higher workload both for the pilots and controllers.

Given the heading angle $\chi(t)$, its variation along a route is computed as

$$\text{heading\_variation} = \int_{t=t_0}^{t_f} \left(\frac{d\chi(t)}{dt}\right)^2 \qquad (2)$$

This yields a measure for the route complexity and allows to compare the routes for O-D-pairs which were computed with respect to different impact parameters, which are given by the scenario design. It is known, that this is strongly related to the individual impact situation, but provides first insights on how to combine different cost terms of a route optimizer in order to reduce the impact on heading variations and therefore route complexity.

Table 2 - Variations of the heading when optimizing for different cost functions

Heading variations / route complexity	wind	wind convection	wind aCCF	wind convection aCCF
Athen - Helsinki	0.03	0.29	0.33	1.35
Cairo - Paris	0.02	0.63	2.7	1.18
Madrid - Tel Aviv	0.02	0.09	0.02	0.08
Madrid - Vienna	0.03	0.24	0.45	2.62

For the route from Athens to Helsinki, the value for route complexity is low when only large-scale wind is considered. If only one of the additional parameters, convection or aCCF, is considered, this value increases to 0.29 and 0.33, respectively. The highest value is reached when both impact factors are used. Still, for the resulting routes, a rather smooth route design is true.

On the route from Cairo to Paris, the routes differ significantly, depending on which impact types were used. Interestingly, the highest value of heading variations occurs when wind and aCCF are considered. This is somewhat surprising as aCCFs are of much larger lateral extend than convective cells. When both aCCF and convection are considered, the optimizer chooses a route with a significant detour, resulting in smaller heading variations.

The routes computed between Madrid and Tel Aviv show that single no-fly-zones or climate sensitive areas can be avoided with a very small lateral detour. Furthermore, all of the computed routes are quite smooth resulting in small values for heading variations.

The routes between Madrid and Vienna, face both smaller-scale impact types which are costly with respect to aCCFs and convective no-fly-zones. While routes, which consider at most one of these impact factors are quite smooth, routes which respects both impact factors have a higher heading variability.

4. Summary and Outlook

In this paper, we presented the first version of our newly created trajectory optimizer. It is built for computing flight routes under consideration of different impact factors like wind, convective no-fly-zones, climate sensitive areas, and potentially further impacts. While considering the combination of impact factors appears trivial in theory – just create a cost function for each of them, and use a weighted sum for the optimization – we sought to understand how the optimizer is impacted if these impact factors have different scales. In future work, this provides insight in how to weight the different cost types according to very individual impact scenarios along the selected route. One important insight is that an approach which only uses optimal control algorithms is doomed to get stuck in local minima, for example if an initial route (segment) lies between two convective cells. If additionally, the initial trajectory lies in an area of higher climate costs, this is likely to result in solutions, which can only respect one single cost type. Generating an initial solution with a graph-based approach avoids this problem. In future research, we extend the functionality of the optimization to optimize 4d-trajectories including A/C related flight performance aspects. The ability to generate optimized flight profiles will have a major impact on the optimality of a trajectory design, especially as the climate impact of contrails massively depends on the flight altitude.

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6. Copyright Statement

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