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Publication date
2022

Document Version
Final published version

Published in
10th International Conference for Research in Air Transportation

Assessing and Modelling Climate Optimal Flights Using Open Surveillance and Remote Sensing Data

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***Abstract*—Sustainability is the biggest challenge facing the aerospace industry today. With the global number of flights expected to rise, the climate impact of aviation will continue to increase. Current research states that the rerouting of aircraft through wind-optimisation for the purpose of fuel usage minimisation and emission reduction is an effective sustainability contribution. However, these routing models only optimize for minimum fuel burn, not necessarily minimum climate impact. Flying efficiently through wind fields could mean flying through regions with higher climate impact, for example, where warming contrails are formed. This potentially forfeits the advantage of the reduced emissions from the wind-optimized route. By bringing together fields such as satellite remote sensing, atmospheric science and aircraft surveillance data, a climate optimized free routing model can be made. This paper creates a climate optimized free routing airspace model by incorporating knowledge from the aforementioned fields and existing wind-optimization models with AI and open-source tools.**

***Keywords*—Sustainability, Remote Sensing, Atmospheric Science, OpenSky, Aircraft Surveillance Data, AI, Contrails**

I. Introduction

As other sectors outside aviation gradually reduce their climate impact, the relative contribution of aviation will rise and the pressure will grow for a more sustainable aerospace industry. Currently, the climate impact of aircraft emissions is significant, approximately 3.5% of anthropogenic climate forcing [1]. Effective sustainability measures for aviation are currently being developed (such as aerodynamic aircraft design and alternative fuels). However, it will take years before these developments can be implemented on a commercially relevant scale. The focus of sustainable aviation should also be on what is safely possible today or within the next few years with the operations of today's aircraft, in order to meet the urgency of the climate crisis. This challenge requires the application of multidisciplinary fields beyond aviation, such as combining global aircraft surveillance data, atmospheric science and satellite remote sensing.

Wind optimization is a quickly implementable and cost-reducing procedure to achieve more sustainable aviation. In general, it is more sustainable, with the simple logic that wind-optimization creates shorter travel times, which uses less fuel and produces the least fuel burn if speed and altitude profiles are also optimal. However, fuel burn optimization is not the same as climate optimization. Less fuel burn might occur because of the shorter flight time, but if more warming contrails (condensation trails) are created during this alternative route, the climate impact may actually increase. Similarly, if cooling contrails were produced, the climate impact would further decrease. This is why climate-optimization is the next step to achieve sustainable aviation.

The climate optimized trajectory model that we present in this paper will include a cost function where the climate impact of the trajectory is compared with alternative trajectories. In order to compare these various trajectories, all climate impacts will be converted to the same unit, radiative forcing (W/m^2). Radiative forcing (RF) provides a unit for the contribution of a greenhouse gas (e.g., CO_2) to the radiative energy budget of the climate system on Earth [2]. This contribution can cause an imbalance in incoming and outgoing energy in the Earth's atmosphere, which leads to an altered equilibrium state of the Earth's climate system.

In this paper, we also present the preliminary results regarding contrail detection model using remote sensing imagery in combination with OpenSky trajectories and wind-optimization using ECMWF ERA5 hourly data.

II. Methodology

Our climate optimised trajectory will be defined as the route with the minimum climate warming impact and maximum cooling impact, thus minimising the added radiative forcing. This would entail the modelled trajectory avoiding regions where warming contrails would occur, or producing cooling contrails on purpose, comparable to geoengineering. Contrails act as extra cirrus clouds and so can have cooling (by reflecting solar radiation) and warming (trapping outgoing terrestrial radiation) effects [3]. When minimizing additional radiative forcing, in some situations it is advantageous to create contrails and in others disadvantageous. The radiative forcing from emissions produced by the detour from the wind-optimized trajectory would have to offset against the radiative forcing gained or lost by warming or cooling contrails.

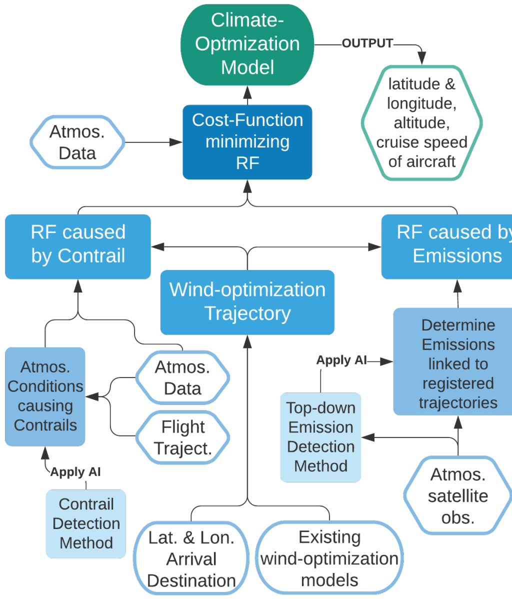

Fig. 1: Flowchart to attain a climate-optimization model

Fig. 1 shows an overview of the process of attaining a climate-optimization trajectory model. The starting point is to study wind-optimized trajectories with reduced fuel consumption, using existing wind-optimization models ([4]–[6]). First, a contrail detection method will be developed based on infrared satellite imagery and machine learning methods. This will allow us to determine the atmospheric conditions under which contrails form, using historical OpenSky and space-based flight trajectory data. Similarly, an emission detection method will be developed. Then, based on historical flight trajectory data and atmospheric satellites, we determine emissions linked to the registered trajectories. The radiative forcing caused by the wind-optimized trajectory will be determined based on the emissions and the contrails of that potential trajectory. Next, the radiative forcing contribution of alternative trajectories will be analysed. The climate-optimized trajectory will be determined using a cost-function, which minimises the added radiative forcing, based on climate metrics (e.g., fuel emissions and contrail impact) dependent on the daily atmospheric conditions. The output is a routing plan, which consists of: latitude and longitude, altitude and cruise speed at several waypoints for each aircraft, assuming a free routing upper airspace.

A. *Climate Optimal Routing*

The simplest form of sustainable flight is based on optimal wind routing. In a wind optimal route, headwinds are avoided, and advantageous tailwind routes are sought out. As such, the total air distance is minimized for a flight. Across the Atlantic flight corridor this is already implemented daily, with westbound flights avoiding the Jet-stream, and eastbound flights seeking it out. Nowadays for optimization a cost index (C.I.) is used which balances flight time and fuel consumption in the cost function. The value of the C.I. varies per airline and type. In this research we focus on fuel-and climate optimized flights.

Because hourly wind field data is available, daily wind-optimized trajectories can be derived, based on aircraft-motion equations ([4]–[6]). To obtain optimal fuel efficiency for a flight, wind optimal routing has to be combined with the most efficient speed and vertical profiles. We will address such challenge using optimal control optimization.

As previously stated, a fuel optimal trajectory does not necessarily imply a climate optimal trajectory. To construct a more accurate climate cost function, we should consider climate effects from emissions and contrails.

B. *Contrail Detection*

The exact extent of contrail's contribution to global warming is still uncertain, but research estimates it to be one of the largest known radiative forcing contribution associated with aviation ([1], [7]), potentially larger than CO_2. Due to the atmospheric similarities between contrails and cirrus clouds, the best channels to detect contrails from satellite imagery are those used to identify cirrus clouds, i.e., Meteosat-11 channels 8.7, 10.8 and 12.0 µm. Since these channels also contain background or ground information, a difference between channels is used to better identify optically thin cirrus clouds. Contrails can be best distinguished in channels 12.0-10.8 or 10.8-8.7, so-called brightness temperature differences (BTD) images [8]. Fig. 2 shows an example of a BTD with contrails.

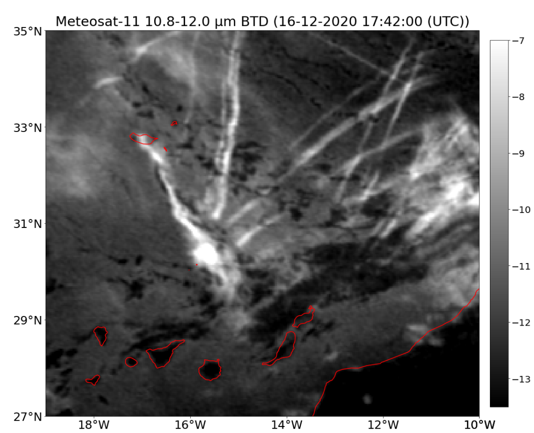

Fig. 2: Meteosat-11 10.8-12.0 µm (BTD) image, the red lines indicate coastlines of The Canary Islands and Morocco

In the SEVIRI Meteosat BTD images, contrails have higher values than background values. Isolating these contrail pixels from background values is similar to plume detection techniques. This is commonly used in atmospheric remote sensing, where emissions from a source cause a plume that is altered in shape due to atmospheric interference, such as wind [9]. The advantage of this method, as opposed to implementing a simple threshold, is that weak plume signals below instrument noise levels are still detectable, since an individual pixel is replaced by a spatial average of the neighborhood of pixels.

The plume detection algorithm in [9] identifies the specific pixels that are significantly larger than the background, using a Z-test. The Z-test compares the normalized difference between the mean value of a neighbourhood of pixels with the background value. In the case of the SEVIRI Meteosat data, this means that the contrail pixels can be distinguished from the lower background value. Applying the plume detection method generates a binary image is where pixels containing contrails have a value of 1, and pixels without contrails have a value of 0. Since the persistence of the contrails is an important climate metric, formation of contrails with a longer lifetime will be attributed additional weight in the cost function.

As the SEVIRI Meteosat is geostationary, it records every 15 min, and thus allows for observing the creation of contrails. By using BTD images and OpenSky ADS-B data, contrails can be detected and linked to the individual aircraft that formed them (examples can be found in the preliminary result section of this paper). When linking individual aircraft with its contrails, more can be learned about the type of contrail forming conditions, such as, temperature, atmospheric pressure, humidity, ice super-saturation (data from EUMETSAT), aircraft altitude (OpenSky). This self-learning contrail detection is input for the cost-function in order to obtain the climate-optimized trajectory model.

Validating this contrail detection method can be done through a local validation model. This local model will consist of photographing the sky for a period of time from a set location. Then, based on the atmospheric conditions on the days which contrails form, we can validate our contrail model. Furthermore, the local validation model may help identify the atmospheric conditions that are missing for contrail prediction.

Overall, we are addressing two key challenges in this part of research, which are how to better combine higher resolution imaging data with flight surveillance data, and how to construct simplified atmospheric contrail formation models for trajectory optimization. To this extent, ground based imagery and low-earth orbit satellite data will also be further explored in this research.

C. Emission Assessment

Using a similar approach to the contrail detection model, we will also address the emission assessment. Currently, this research has being conducted using a bottom-up approach ([10]–[12]), as opposed to a top-down approach. In this bottom-up approach, registered flight trajectories of individual aircraft are combined with aircraft performance and emission models. This leads to an assessment of the registered aircraft engine emissions of CO_2, NO_x, H_2O, CO, SO_x and HC (hydrocarbons). Unfortunately, these registered flight inventories are incomplete. Global coverage to track flights over the oceans is limited. Such data gaps require estimations of the travelled flight trajectories, which can underestimate these in terms of travelled distance, thus underestimating emissions.

Another way to get this emission assessment in this research is the top-down approach, as a way to sidestep some of these issues. The top-down approach is characteristic for remote sensing, and will be used in this project. By detecting the emissions through atmospheric satellite observations, linking them to areas of heavy density traffic, an emission assessment can be made. Validation will be done through the bottom-up approach of OpenAP [13].

III. Preliminary Results

In this section, we present some preliminary results of our climate-optimized model, specifically regarding the modules for wind-optimal routing generation and contrail detection.

A. Wind-optimised flight

In Fig. 3, a registered EUROCONTROL flight is compared with a wind-optimized flight that we generated, in terms of time and distance traveled. The wind field data used is from an hour before takeoff, in order to make it implementable in a flight plan. While the calculated wind-optimized flight time is shorter than the registered flight time, the travelled distance of the wind-optimized trajectory is longer, thus more sustainable. This wind-optimized trajectory is our starting point for our individual flight climate-optimized model, assuming free route airspace and another form of separation assurance than the current procedural separation.

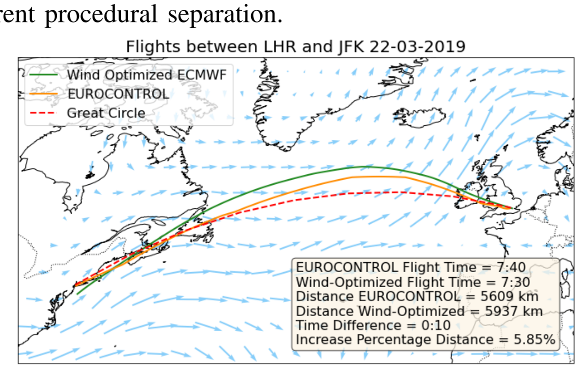

Fig. 3: Comparison of EUROCONTROL registered flights and wind-optimized trajectories for 22-03-2019 between Heathrow and JFK

B. Contrail detection

The SEVIRI Meteosat has a cycle time of 15 minutes for all channels. This high temporal coverage allows for generating an animation of the contrail formation, by playing the images one after the other. The resultant animation shows the formation of contrails and the possibility for tracking the duration of contrails, using Z-method [9]. The duration of contrails is relevant for the extent of their climate impact.

OpenSky uses ADS-B data, which allows for a high temporal and spatial coverage, and thus can be integrated in this SEVIRI Meteosat contrail animation. The spatial coverage of OpenSky is best assured for Europe and North America, whereas, the coverage over the oceans is minimal, due to the nature of terrestrial ADS-B. Space-based ADS-B will also be used to improve the coverage over the oceans.

Three examples of OpenSky flight trajectory data together with a BTD image, are shown in Fig. 4. These three sequential images show flight RYR5QR (Lisbon to Dublin) fly to the northeast and the contrail subsequently creates. This created contrail is blown to the east by wind (as confirmed by ECMWF wind data).

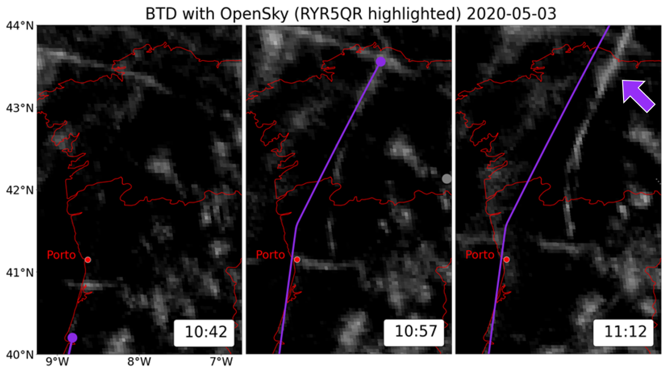

Fig. 4: Meteosat-11 10.8-12.0 μm (BTD) image at 03-05-2020 from 10:42:00 to 11:12:00 (UTC), with OpenSky trajectory of RYR5QR, near Porto, Portugal, formed contrail indicated by purple arrow.

IV. Conclusion and Challenges

We present the first steps necessary for creating a climate optimized routing model based on wind-optimization models and minimizing for warming and maximizing for cooling radiative forcing of contrail and emission effects. Our preliminary results have shown that linking individual aircraft with their contrails is possible. Future work will combine this method with self-learning AI and open-source atmospheric data to identify conditions under which contrails form.

Besides developing this contrail detection method, an emission assessment will be made on the basis of atmospheric satellites (TROPOMI, OCO-2 and SEVIRI Meteosat). From this emission assessment, we can determine the expected emissions from aircraft trajectories. Once the expected climate impact from contrails and emissions from aircraft trajectories is known, this can be implemented in the cost-function, the starting point being the wind-optimized trajectory. This cost-function will produce a climate-optimized trajectory.

Although our top-down approach has many advantages, the methodology described above comes with some limitations and challenges. As is emblematic for atmospheric remote sensing measurements, the emission assessment typically contains background values that could be unrelated to aviation. Over the mid-Atlantic, emissions from cities or industry are expected to be minimal, except for shipping vessels. By calibrating the model over the oceans, and then extrapolating this globally, a universal model can be obtained. This still means the accuracy of the obtained model is uncertain over land, however a validation can be done based on the bottom-up approach, as well as on the local validation model.

Contrails with a lifetime of less than 15 minutes cannot be incorporated into the model, since this is outside the temporal resolution of SEVIRI Meteosat. However, contrails with short lifetimes create little additional radiative forcing, and can reasonably be omitted.

Currently, our goal is to focus on the optimization of individual trajectories. Although this assumes a free routing airspace not currently practiced, it is possible given technological feasibility. This will contribute to our further goal of climate-optimal flight networks.

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