Quantum Climate Challenge 2022 - Reducing the climate impact of air travel via optimized routing

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1 Goal of the challenge

The Deloitte Quantum Climate Challenge 2022 aims to explore how the contribution of air travel to the anthropogenic (human made) climate change can be reduced by optimizing flight trajectories using quantum, quantum-classical hybrid, or quantum inspired solutions. The challenge scenario includes a traffic sample of multiple flights with various paths and schedules. The flight trajectories are to be optimized so that the overall warming climate effect considering all flights is minimal while being compliant with flight safety regulations. Different climate effects depending on the fuel burn, the geographical location, altitude, weather conditions and timings are to be considered. A detailed problem motivation as well as a description of the mathematical formulation and the constrains are given in this document.
Please be aware that assumptions and simplifications were made to allow the development of a solution concept and a first algorithm within the given time frame of this challenge. This concerns in particular - but not exclusively - the description of the flight parameters and flight regulations.

2 Background

2.1 Climate effects due to air travel

Climate change effects all of us. A major contributor is the fast growing industry of air travel. Between 1970 and 2017 the number of airplane passengers grew from 100 Million to 4 Billion. During the same time span improvements such as advanced technology, better air traffic control, and denser seating configurations reduced the energy consumption per passenger mile by 75 %. Nevertheless, air travel was still responsible for 905 Million tons of CO_2 emissions in the year 2018. This is equivalent to 2.4 % of the global CO_2 emissions and the amount is increasing over the years. [Ove19]

Air travel has further effects on the climate besides CO_2 emissions. This includes NO_x emissions, water vapor emissions, contrail cirrus, and aerosol interaction with radiation and clouds. A schematic of the effects is shown in figure 1. All effects considered in this challenge are described below. For more detailed descriptions of the effects please refer to, e.g. Lee et al. [Lee+21]

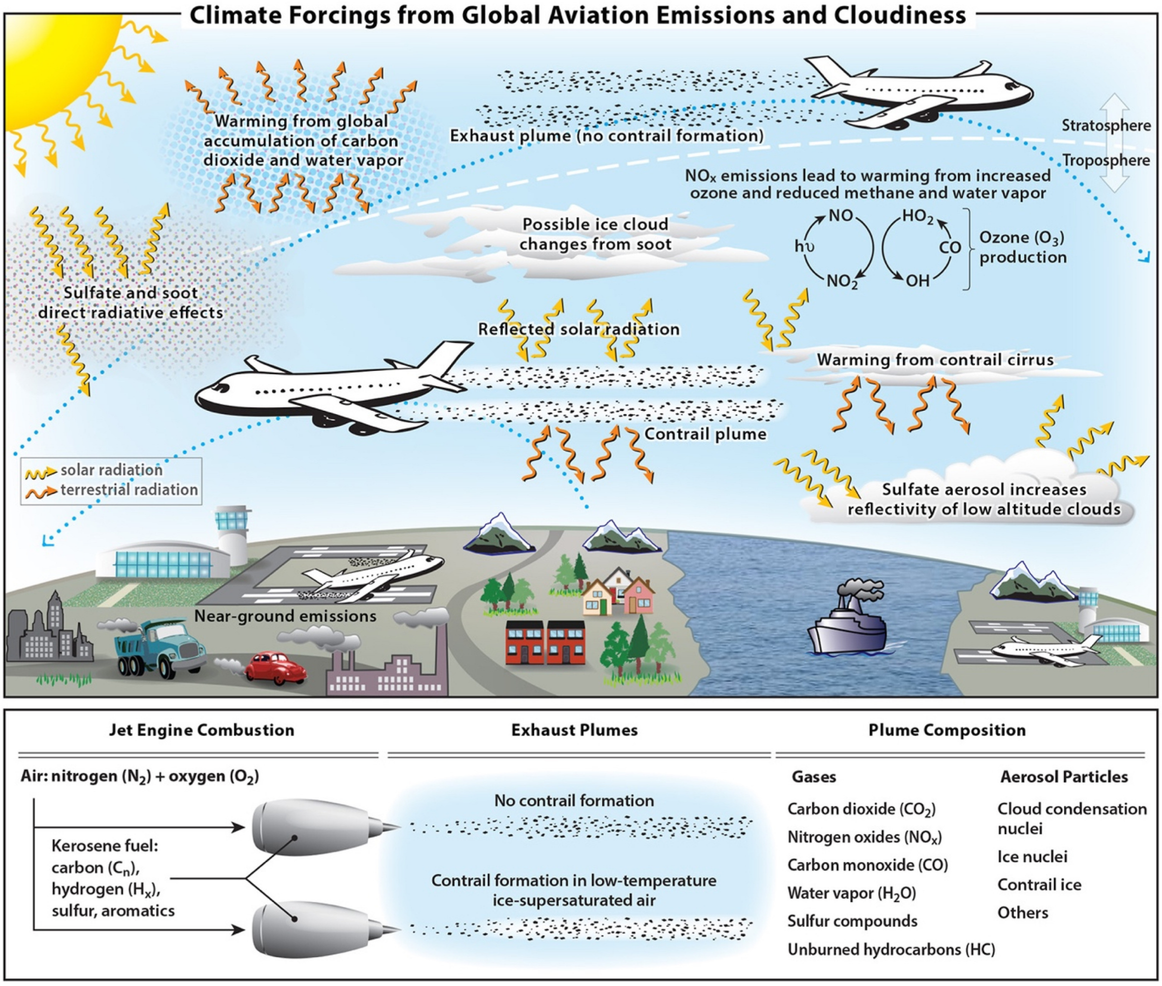

Figure 1: This figure gives a schematic overview of the climate effects of air travel. The effects can be split into net positive (warming effects) and net negative effects (cooling effects). The following effects contribute to the net warming: CO_2, NO_x, water vapor, soot emissions and contrail formation. Cooling effects come from the production of sulfate aerosol production. Net effects are considered because NO_x emissions and contrails can have both a warming and a cooling effect. Overall both contribute more to warming. This figure was published by Lee et al. in [Lee+21].

To evaluate the climate effects of air travel appropriate metrics to quantify the impact have to be identified. The impact depends on the longevity of the emitted substances as well as the timing and location of the emission. Commonly used metrics are the Global Warming Potential (GWPs) and the Global Temperature Change Potentials (GTPs). These metrics are based on the radiative forcing (RF) or effective radiative forcing (ERF) and the lifetime of the substance. Both are usually estimated as the average global effect for a whole year. [Fug+10]

Radiative force (RF) is defined as the change in energy flux in the atmosphere due to natural or anthropogenic drivers of climate change in the units $\frac{\mathrm{W}}{m^2}$. It is usually defined as the flux changes at the top of the atmosphere (TOA) or at the tropopause. The sustained RF can be related to the global mean temperature as $\Delta T = \lambda \mathrm{RF}$, with λ being a climate sensitivity parameter. The RF is a good estimation on the climate effect for many forcing agents (green house gases). However it does not take rapid adjustments in the troposphere into account. These may have an enhancing or reducing effect on the flux and thus having an effect on the climate response. The effective radiative forcing (ERF) takes this into account and is thus a more precise measure. The ERF and RF are helpful measures to estimate and compare how drastic the effect of a certain contributor is. [Cli14] The different estimated ERF for different effects of air travel on our environment are given in the descriptions below. For comparability the ERFs of all below described effects are estimated globally and for the year 2018.

2.1.1 CO_2 emission

CO_2 is one of the most prominent green house gas. It is emitted from the combustion of jet fuel in aircraft engines. The amount of CO_2 emitted is defined by the emission index 3.16 $\frac{\mathrm{kg}}{\mathrm{kg\ fuel}}$ and depends on the type of fuel an engine used. Using different models the resulting estimated ERF for 2018 globally for CO_2 is 34.3 $\frac{\mathrm{mW}}{\mathrm{m}^2}$. [Lee+21] The climate effect of CO_2 is particularly large as it is very long-lived, with around 50 % of emitted CO_2 still in the atmosphere after 50 years. [Sto+13]

2.1.2 Nitrogen oxide (NO_x) emissions

Nitrogen oxide ($NO_x = NO + NO_2$) is formed by oxygen and nitrogen reacting with each other at high temperatures as in the combustion engines. It is emitted into the atmosphere during the flight. [Fug+99] The emitted NO_x forms ozone O_3 in a catalytic reaction. Ozone is a green house gas which in the long term view results in a positive ERF and a warming effect. Further NO_x reduces the levels of CH_4, another green house gas resulting in a cooling effect. [RFG20] Both warming and cooling effects need to be taken into account when looking at the total contribution of NO_x, called the net-NO_x. The total emitted amount is estimated as 15.14 $\frac{\mathrm{g}}{\mathrm{kg\ fuel}}$. This is depending on the used engines and fuels. In 2018, the net-NO_x emissions resulted in an ERF of 17.5 $\frac{\mathrm{mW}}{\mathrm{m}^2}$. [Lee+21]

2.1.3 Water vapor emissions

The amount of water vapor emitted during air travel is estimated to be around 1.231 $\frac{\text{kg}}{\text{kg fuel}}$. The added and accumulated water vapor changes the humidity in the respective atmosphere layers. This in turn changes the radiative balance in these layers. The lower stratosphere and tropopause are particularly affected by this. The ERF of water vapor is complicated to assess as it depends a lot on the vertical and horizontal distribution of the vapor. Further, the heights for the different layers can vary depending on the season making it even more complicated. The resulting ERF of the water vapor ERF was estimated to be 2.0 $\frac{\text{mW}}{\text{m}^2}$ in 2018. [Lee+21]

2.1.4 Contrails

Air travel has an effect on the cloudiness in the upper troposphere. This comes from contrails induced by airplanes. They occur when the ambient atmosphere is supersaturated with respect to ice (so called ice supersaturated regions or short ISSR). The contrails can cause contrail cirrus. Contrails can have a cooling effect for short wave lengths (UV) and a warming effect for long wavelengths. However, during the night the effect of contrails is always warming. [Lee+21] The cooling effect may also arise from a decrease in natural cloudiness. In total the net radiative forcing effect is positive and it is the largest single radiative forcing component with respect to air travel. [BK11] As mentioned before, contrails occur in areas which are ice supersaturated. These areas vary greatly in the temporal and spatial domain. Typically the ice supersaturated regions (ISSR) are at around 300 hpa during summer and autumn and at 340 hPa during winter and spring. The size of these areas is typically $1 - 2$ km vertically and 150 ± 250 km horizontally. [Man] If a contrail is created and has a positive or negative effect on the climate is thus dependent on the timing and location of the airplanes. This complex and high dimensional problem makes it hard to calculate the effects of contrails. Using some assumptions Lee et al. estimate the ERF of contrail cirrus to be 57 $\frac{\text{mW}}{\text{m}^2}$ on average in 2018. [Lee+21]

2.1.5 Other effects

There are other effects arising from the emissions of aerosols from the combustion engines. These aerosols interact with radiation and clouds. The dominant source of aerosols are soot and sulfate aerosols, where soot is a condensation of unburned fuel and is made up of BC (black carbon)and OC (organic carbon). The sulfate aerosols stem from the oxidation of sulfur in the air planes fuel and is emitted as SO_2 and H_2SO_4.

The aerosols interact with the radiation: short wave radiation is absorbed by the soot leading to a warming effect. On the other side sulfate aerosols scatter the short wave radiation leading to a cooling effect. The ERF is estimated to be 0.9 $\frac{\text{mW}}{\text{m}^2}$ for soot and -7.4 $\frac{\text{mW}}{\text{m}^2}$ for sulfate in 2018. [Lee+21]

The aerosols naturally interact with and may influence the formation of clouds. Especially sulfate is an efficient cloud condensation nuclei, meaning clouds form around it. Different positive and negative effects arise from the formation of clouds. However there are very high uncertainties when estimating the ERF for cloud interactions with aviation soot and sulfate. [Lee+21]

As the uncertainty of both above mentioned effects are very high, they are not included further in the challenge and are just described for completeness. As soon as a suitable model for the climate effects is available it can easily be included to the algorithm analog to the other climate effects.

2.1.6 Previous work

The optimization of flight trajectories with respect to the climate effects was already investigated in the two European funded research projects REACT4C and WeCare, where a mathematical model was derived to calculate the optimal trajectory. A grid was introduced dividing the world and atmosphere into squares. The conditions were assumed to be constant within one grid point but may vary to others. The route per flight was then chosen so that the overall climate effect considering all grid points was minimized. [Gre+14]
It was found that with small changes in the trajectory of a flight its climate effects could be reduced by 25 % with only a slight increase in fuel and a 0.5 % increase in the operating costs. Please refer to Lee et al. for a detailed description. [Kli21]

2.2 Basic flight parameters

When optimizing flight trajectories for a minimal climate effect it is required to comply to all flight safety regulations. To succeed in this a basic understanding of the safety rules is needed. Flight safety regulations differ between countries and continents. The constrains given in this challenge in section 3.2 follow the regulations of the German air traffic control (DFS Deutsche Flugsicherung GmbH).

Distances in the air travel domain are commonly measured in nautical miles (NM), the speed is usually given in knots. Speed can also be measured in the mach number $M = \frac{u}{c}$ represented by the ratio of the current speed u divided by the speed of sound c in the current medium. A mach number smaller than 1 means it is always slower than the speed of sound. The altitude is given in feet or flight levels. It is measured using a barometric altimeter with a standard reference pressure of 1013.25 hPA as the ground pressure. The altitude is calculated using the pressure difference between the reference and the measured pressure and the barometric formula. The resulting altitude in feet is often translated into flight level by dividing it by 100 assuming the standard reference pressure. Due to different weather conditions the pressure can vary strongly. Since this effect is equal for all planes in the same location the necessary distances can still be guaranteed.

The speed of the airplane depends on the atmospheric conditions, specifically on the pressure. The lower the pressure the faster the minimum speed of the airplane so that it does not stall and drop. Because the speed of sound decreases with a decrease in temperature, the maximum speed of the airplane also decreases with the temperature, as it is not favorable to pass the speed of sound. This results in a triangle for the minimum and maximum speed with regards to altitude. There is one point where minimum and maximum speed are equal. This is called the coffin corner as it is dangerous to fly at these altitudes. As a safety precaution the maximum allowed altitude of 410 FL (flight level) lies safely below this. The ground speed (GS) is the reference speed of the airplane in a fixed ground reference system. The true air speed (TAS) is equal to the ground speed (GS) but with a correction for the wind component.

$$\overrightarrow{GS} = \overrightarrow{TAS} + \overrightarrow{Wind} \tag{1}$$

A flight path is planned along discrete flight points. In our challenge these are spread out over Europe. Here, we are looking at the distance flown between two points in cruise mode, meaning we assume the airplane is already at a traveling height and are explicitly excluding the start and landing phases of the flight. Thus, the trajectories we are investigating in this challenge begin at a fixed point and end at a fixed point which are both defined at a given flight level above ground. In real life, currently an optimal route for a flight is regarded as the shortest possible distance flown between start and landing without considering climate impacts. Deviating from this approach, in our challenge we want to optimize the flight trajectories for an overall minimal negative climate impact.

3 Problem Modeling

3.1 Target parameter

As stated, the aim of this challenge is to minimize the total contribution of air travel to the anthropogenic climate change by optimizing flight trajectories. This can be achieved because many of the described warming effects caused by air travel are dependent on the location, altitude, weather conditions and timing. Changing the route or altitude can thus reduce the effect a flight has on the climate. In some rare cases even a cooling effect can be induced.

The effects of flights on the climate can be quantified as rise ΔT (in Kelvin) of the global temperature. This rise in temperature ΔT is the target parameter that should be optimized to a minimum over all flight trajectories. This rise in temperature ΔT can be derived from the climate effect ΔC in Kelvin per kg of fuel. ΔC is given in the dimension $10^{-12}\ \frac{\mathrm{K}}{\mathrm{Kg\ fuel}}$.

3.2 Flight path assumptions

The flight path is typically modeled along a set of discrete points as geographical coordinates which enables the tracking of the flight in a 2D plane. Next, the altitude of the airplane is added. Thus, the flight path is tracked as a list of geographical points passed including the time stamp when it was passed and the altitude at which it was passed. As mentioned before the altitude is given in feet or flight level (feet/100 when we assume standard atmospheric pressure). For this challenge we assume the following typical flight levels in the range of FL 100 - FL 400.
Further constrains are posed by the safety distances required between each airplane. Vertically the minimum distance between two airplanes is 1000 ft. The horizontal minimum distance between two airplanes is more complex and depends on the size of the airplane. For this challenge we make the assumption that all airplanes have the same mass and the minimal distance between them needs to be a minimum of 5 NM independent of the altitude.

For this challenge only the Airbus A320 airplane with the following specifications is used.

- range: 3.300 NM
- length: 37.57 m
- maximum altitude: 41000 ft

An approximate fuel consumption and TAS speed at different flight levels of the A320 was published by the European Organization for the safety of air navigation: Eurocontrol. For this challenge the Base of Aircraft Data (BADA) Revision 3.0 is used. This specifies the true air speed, rate of climb/decent and fuel flow for the cruise, climb and decent at a range of flight levels. For simplicity in this challenge the plane weight is set to be constant and nominal at 62000 kg. The data is based on a total-energy model and BADA 3.0 performance coefficients. [NPM10] It will be available for download including a detailed description of this data for registered participants of this challenge.
The radius for a change of direction of an airplane can be calculated as

$$r = \frac{v^2}{gtan(\beta)}, \tag{2}$$

where g is the gravitational acceleration $g = 9.81\ \frac{\mathrm{m}}{\mathrm{s}^2} = 32\ \frac{\mathrm{ft}}{\mathrm{s}^2}$, β is the angle of inclination of the airplane and v the true air speed. Please be aware of the units for true air speed, g and the resulting radius r. For this challenge the maximum inclination angle is $\beta = 25°$. Any trajectory including turns below this radius will not be allowed. The actual turn radius of an airplane during a flight also depends on the pressure [770] but for simplification we use equation 2.

3.2.1 Atmosphere

For this challenge a rectangular grid is put above Europe to discretely describe the atmosphere. This is illustrated in figure 2. Each grid voxel is localized using the center point as the position. The horizontal grid points are spaced with 2°E and 2°N. The limits are: south: 34°N; north: 60°N; west: 30°W; east: 30°E. The steps are given in degrees where 'a' are the steps from west to east and 'b' are the steps from south to east. This gives 31 voxels thus 30 steps 'a' from west to east and 14 voxels thus 13 steps 'b' from south to north. Further, the grid has 14 discrete vertical voxels given in FL. The flight levels start at FL100 and go up to FL400 in 13 discrete steps 'c' of FL20 each. Overall there is a total of 6076 voxels making up the total possible air space and the atmosphere. As mentioned in section 3.1, the effect of a flight can be described using the climate effect ΔC. A specific value for ΔC can be assumed to be constant within the whole grid voxel. This includes effects $\Delta C_{\text{non-}CO_2}$ caused by all non-CO_2 emissions in $10^{-12}\ \frac{\text{K}}{\text{Kg fuel}}$ as well as ΔC_{CO_2} for the CO_2 emissions.

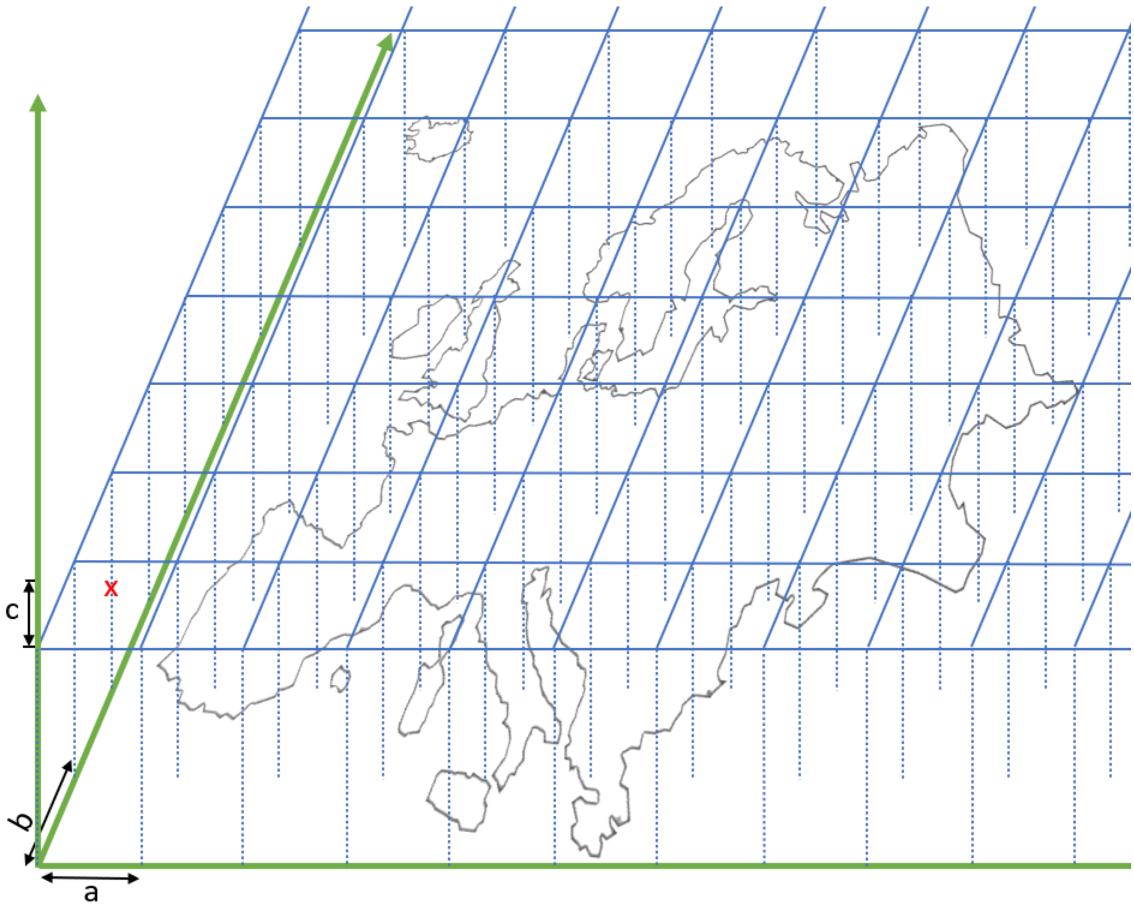

Figure 2: This schematic shows the applied grid over Europe for one flight level. The lowest most south west point is indicated with the red x.

3.3 Data

Data and a detailed description of it will be made available for download for registered participants of this challenge on March 4th, 2020.

4 Mathematical Description

The cost function for the climate impact is defined as

$$\Delta T = \sum_{i,j} (\Delta C_{\text{non-}CO_2}(i,j) + \Delta C_{CO_2}) * F(i,j), \tag{3}$$

resulting in a total rise in temperature in Kelvin for each flight i and voxel j. $F(i,j)$ is the consumed fuel of flight i in the voxel j. $\Delta C_{\text{non-}CO_2}(i,j)$ and ΔC_{CO_2} are the rise in temperature for non-CO_2 and CO_2 effects. The overall aim is to minimize the rise in temperature ΔT in Kelvin considering all flights and thus minimizing ΔT.

5 Challenge Tasks

To successfully complete this challenge please complete the following tasks:

1. Create a quantum algorithm, a quantum hybrid solution or a quantum inspired solution addressing the optimization of the flight trajectories with respect to a minimum effect on the climate. The trajectory for each airplane is defined as a list of points, altitudes, and time stamps, where the first point is the actual starting time and the last point the actual arrival time. Both quantum annealing and gate based is fine.

2. Compare your quantum solution to that of a classical computer describing advantages and disadvantages of the approaches. Evaluate the performance differences of your solution vs a classical approach.

3. Discuss the requirements for your solution to be implemented in real life and give an estimation of the time horizon. Requirements can e.g. be the number of logical qubits needed, coherence times, external (real time) inputs like weather predictions, connections to flight control systems and others.

4. Give an overview of your research and the resources used during the challenge.

5. Run a (scale down) version of your quantum algorithm on a quantum computer or simulator. You may use the 7 qubit gate based quantum computer provided by IBM or different quantum computers of your choice.

The challenge will be evaluated using the following evaluation criteria:

- Number, comprehensiveness, and adequacy of fulfilled tasks considering the challenge aim and setting. – 20%

- Degree of innovation of the approach, concept, and algorithm including creativity and originality. – 25%
- Feasibility, usefulness and functionality of the approach, concept, and algorithm – 25%
- Quantum community impact – will your solution lead to progress within the quantum community e.g. create new applications or projects, spark discussions, increase public interest and knowledge about quantum? - 15%
- Presentation and structure of the results – 15%

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