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COMPARISON OF VARIOUS AIRCRAFT ROUTING STRATEGIES USING THE AIR TRAFFIC SIMULATION MODEL AIRTRAF 2.0

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Abstract. A climate-optimized routing is expected as an operational measure to reduce the climate impact of aviation, whereas this routing causes extra aircraft operating costs. This study performs some air traffic simulations of nine aircraft routing strategies which include the climate-optimized routing, and examines characteristics of those routings. A total of 103 trans-Atlantic flights of an Airbus A330 is simulated for five weather types in winter and for three types in summer over the North Atlantic by using the chemistry-climate model EMAC with the air traffic simulation submodel AirTraf. For every weather type, the climate-optimized routing shows the minimum climate impact, whereas a trade-off exists between the costs and the climate impact. The cost-optimized routing lies between time- and fuel-optimized routings, and minimizes the costs. The aircraft routing for minimum contrail formation shows the second-lowest climate impact, whereas this routing also causes extra costs.

Keywords: Climate impact of aviation, Climate-optimized routing, North Atlantic weather patterns

INTRODUCTION

A climate-optimized routing has been examined to reduce the climate impact of aviation. This routing significantly reduces the climate impact by optimizing flight routes to avoid regions where released emissions and formed contrails have a large climate impact. Previous studies show that the climate-optimized routing greatly decreases the impact, whereas the routing increases aircraft operating costs (Grewe *et al.*, 2014, Ng *et al.*, 2014). Thus, if additional costs for the climate impact of aviation, such as environmental taxes, are included in the current operating costs, a cost increase due to the climate-optimized routing is possibly compensated. This inclusion can change the current routing strategy of minimum costs and incentivize airlines to introduce a climate-optimized flight planning. This study simulates 103 trans-Atlantic flights for not only the climate-optimized routing but also different aircraft routings by using the chemistry-climate model EMAC (Jöckel *et al.*, 2010, 2016) with the air traffic simulation submodel AirTraf (Yamashita *et al.*, 2016, 2019). The simulations are performed for representative weather types over the North Atlantic and common characteristics of those aircraft routings are examined.

METHODOLOGY

To analyze weather patterns over the North Atlantic, a ten years EMAC simulation was carried out for the time period from December 2008 to August 2018 (Table 1). The EMAC model is a numerical chemistry and climate simulation system that includes submodels describing tropospheric and middle atmosphere processes and their interaction with oceans, land, and influences coming from anthropogenic emissions (Jöckel *et al.*, 2010, 2016). EMAC comprises the Modular Earth Submodel System MESSy (version 2.54) to link multi-institutional computer codes and the 5th generation European Centre Hamburg general circulation model ECHAM5 (version 5.3.02; Roeckner *et al.*, 2006). For this study, the model was nudged towards the realistic meteorology (ERA-Interim reanalysis data; Dee *et al.*, 2011).

Next, air traffic was simulated by coupling of AirTraf (version 2.0; Yamashita *et al.*, 2019) with EMAC. AirTraf consists of the total energy model, the DLR fuel flow correlation method and a genetic algorithm. A flight trajectory is optimized including altitude changes according to a selected aircraft routing strategy (called an option): great circle, flight time, fuel use, NO_x emission, H_2O emission, contrail formations, simple operating cost, cash operating cost (COC), and climate impact estimated by the algorithmic Climate Change Functions (aCCFs;

Van Manen, 2017, Yin *et al.*, 2018, Van Manen and Grewe, 2019). These options represent the objects to be minimized (we abbreviate the options to, e.g. the 'climate option'). AirTraf considers only a cruise flight phase; trajectory conflicts and operating constraints are neglected. Further details are given by Yamashita *et al*. (2016, 2019).

Table 1. Model setup for EMAC and AirTraf models

Parameter	Description
ECHAM5 resolution	T42L90MA (2.8° by 2.8° in latitude and longitude, up to 0.01 hPa)
Simulation period	Dec. 2008-Aug. 2018 (ten years), representative days (Table 2)
Flight plan	103 trans-Atlantic flights (52 eastbound/51 westbound)
Aircraft/engine type	A330-301/CF6-80E1A2, 2GE051 (with 1862M39 combustor)
Mach number	0.82
Flight altitude change	[8.8, 12.5] km (fixed at 10.7 km for the great circle option)

NORTH ATLANTIC WEATHER PATTERN ANALYSIS

Weather patterns were classified into types from the ten years EMAC calculation, which provided ten complete winters (December, January and February) and summers (June, July and August). Diagnostic indices of the North Atlantic Oscillation (NAO) and the East Atlantic (EA) were calculated by considering a similarity of daily-mean geopotential height anomalies at 250 hPa to typical NAO and EA teleconnection patterns over the North Atlantic (80°W-0, 30°N-75°N; Woollings *et al.*, 2010, Irvine *et al.*, 2013). The indices characterize a jet stream position and strength, so that all days of the ten complete winters and summers are classified into five types for winter (W1-W5) and three types for summer (S1-S3). Table 2 lists the types and the representative days for each type; for example, when observing type W3 (Fig. 1), we see that blocking over southwest Europe occurs and diverts the jet stream to the north. As a result, the jet stream becomes weak and tilts southwest-northeast.

Table 2. North Atlantic weather types for winter and summer. This classification refers to Table 1 of Irvine *et al.* (2013). "+" and "–" stand for positive and negative values.

Type	NAO/EA indices	Jet stream position/strength	Representative day in 2008-2018
W1	EA+	Zonal/strong	January 12, 2010
W2	NAO+	Tilted/strong	January 1, 2015
W3	EA–	Tilted/weak	January 9, 2012
W4	NAO–	Confined/strong	December 20, 2009
W5	Mixed	Confined/weak	February 19, 2012
S1	EA+	Zonal/strong	July 11, 2009
S2	Mixed	Weakly tilted/weak	August 1, 2016
S3	EA–	Strongly tilted/weak	July 26, 2011

AIRCRAFT ROUTING CHARACTERISTICS

Some simulations of the nine aircraft routing options were carried out for the trans-Atlantic flights for every representative day (Table 2). Here, we briefly illustrate three characteristics of those routings with the calculation for type W3, focusing on relative changes (in %) to the calculation obtained by the COC option. First, the COC and the climate options are analyzed. COC for the COC and the climate options are 5.35 and 5.85 Mil.USD, whereas the estimated

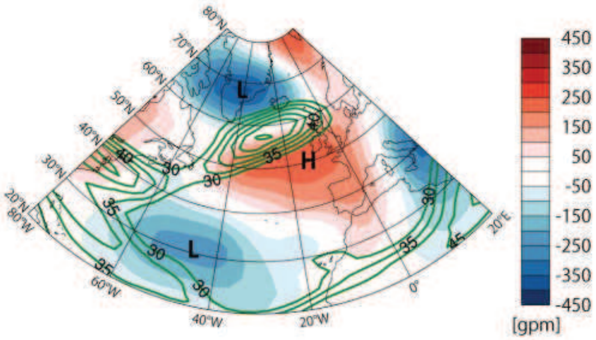

Figure 1. Daily-mean geopotential height anomaly (red-blue contours) and zonal wind above 30 m s^{-1} (green contours) at 250 hPa on January 9, 2012 (type W3)

climate impact $ATR20_{total}$ (the average temperature response over 20 years) of the two options are 4.1×10^{-7} and 1.8×10^{-7} K, respectively. The climate option decreases $ATR20_{total}$ by 56.5 % (Fig. 2) with an extra COC of 9.2 %. Of the nine routing options, the climate option shows the lowest $ATR20_{total}$, whereas a trade-off is observed between the cost and the climate impact. This trade-off agrees with that indicated by the previous studies.

Second, the time, the fuel and the COC options are compared. To minimize COC, a reduction of both flight time and fuel is desirable, because COC depends on the two factors; however, a trade-off generally exists between them. For type W3, the time penalty of flying minimum fuel trajectories is 1.4 percentage points (%pt), whereas the fuel penalty of flying minimum time trajectories is 14.8 %pt. On the other hand, the COC option takes 1.3 % more flight time (with 14.7 % less fuel) than the time option takes, and consumes 0.07 % more fuel (with 0.09 % less flight time) than the fuel option consumes. The COC option lies between the time and the fuel options, and yields the best compromised values of the flight time and the fuel to minimize COC (COC for the time and the fuel options are 5.60 and 5.36 Mil.USD).

Last, the contrail option shows the second-lowest $ATR20_{total}$ of 2.9×10^{-7} K, which corresponds to a decrease in $ATR20_{total}$ by 30.7 % (Fig. 2); however, as with the climate option, this option increases COC by 9.3 % (COC for the contrail option is 5.9 Mil.USD). The point is that these three characteristics are common to every representative day (the quantitative values of the relative changes vary with the days).

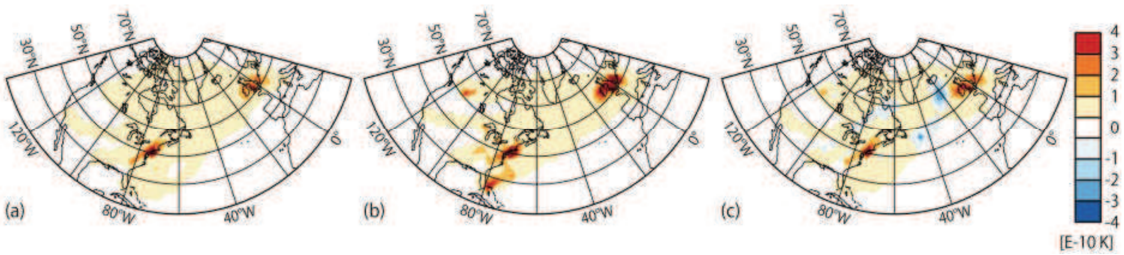

Figure 2. Estimated climate impact ($ATR20_{total}$) for contrail (a), COC (b) and climate routing options (c) on January 9, 2012 (type W3)

CONCLUSIONS

Weather patterns over the North Atlantic were classified into five types for winter and three types for summer from the ten years EMAC calculation, and representative days for each type were selected. The EMAC/AirTraf calculations for those days revealed the common characteristics of the aircraft routings. The climate option reduces $ATR20_{total}$ most and shows a trade-off between COC and $ATR20_{total}$; the COC option lies between the time and the fuel options and achieves the minimum COC successfully; and the contrail option shows the second-lowest $ATR20_{total}$, which causes an increase in COC.

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REDUCING AVIATION EMISSIONS AND FUEL BURN BY RE-ROUTING TRANSATLANTIC FLIGHTS

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Abstract. After decades of limited situational awareness in the mid-North Atlantic, full satellite coverage will soon be available. Routes could now be altered to exploit the wind field fully and reduce fuel use. When aircraft speed and altitude are constant, the fuel flow rate per unit time is also constant and the optimal route has the minimum journey time. Here we show that changes to current practice could significantly reduce fuel use.

Flights between New York and London, from 1st December, 2019 to 29th February, 2020 are considered. Optimal control theory is used to find the minimum flight time through wind fields from a global atmospheric re-analysis dataset. The aircraft is assumed to fly at Flight Level 340 with airspeeds ranging from 200 to 270 m s^{-1}. Since fuel burn and greenhouse gas emissions are directly proportional to the product of time of flight and airspeed, this quantity, air distance, is used as a measure of route fuel efficiency.

Minimum time air distances are compared with actual Air Traffic Management tracks. To allow clearer comparisons between the fuel efficiency of daily ATM tracks and optimised routes a new quantity, W_{route}, is introduced. This is defined as the ratio of the average headwind along the route to the airspeed. Potential air distance savings range from 0.9 to 7.5% when flying west and from 0.8 to 16.3% when flying east. Thus large reductions in fuel consumption and emissions are possible immediately, without waiting decades for incremental improvements in fuel-efficiency through technological advances.

Keywords: route optimisation, fuel efficiency, ATM tracks, minimum flight time, mid-North Atlantic wind field