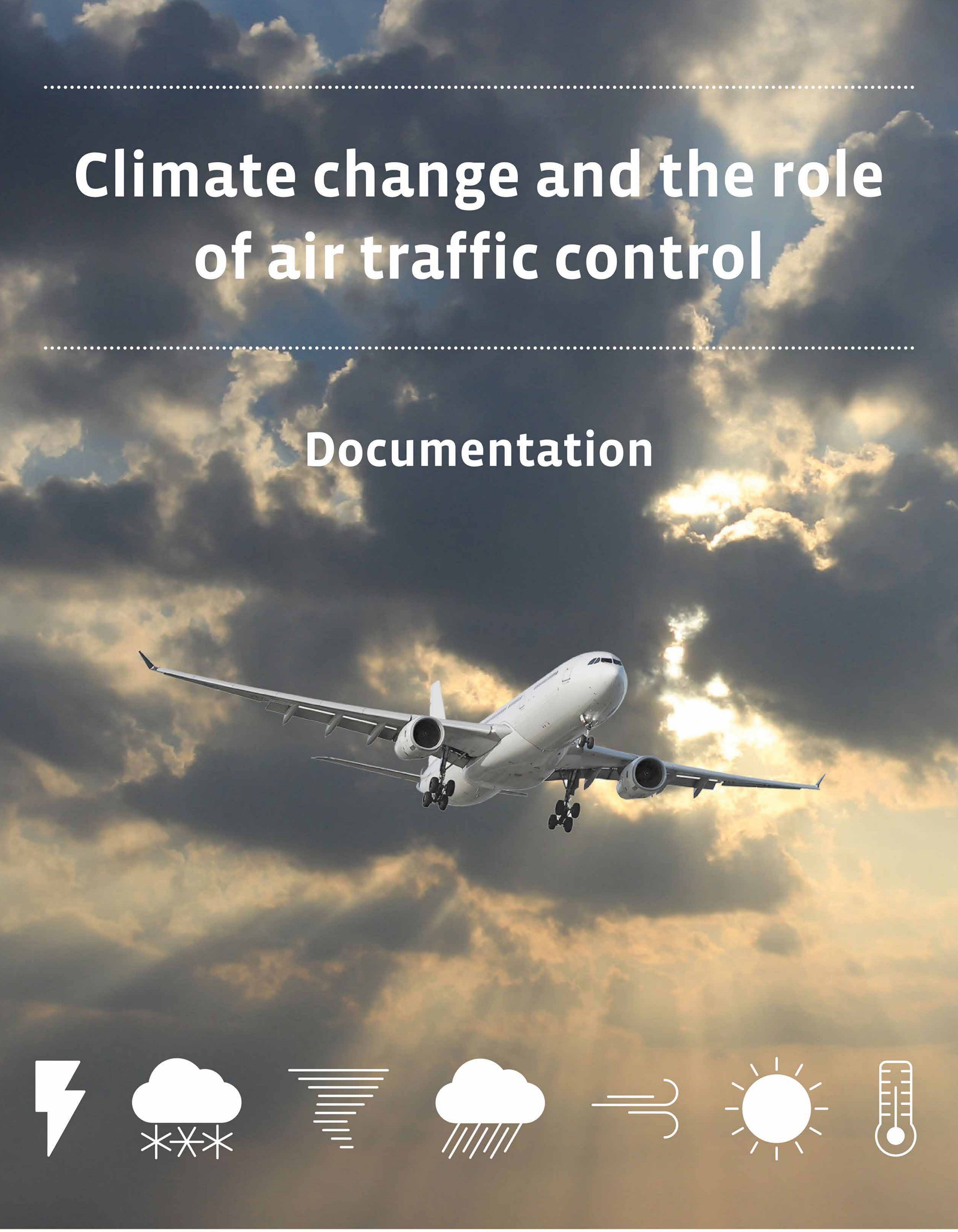

Climate change and the role of air traffic control

Documentation

Baltic FAB
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VILNIUS TECH
Vilnius Gediminas Technical University

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FABEC

Editorial

Climate change and the role of air traffic control – turning new scientific evidence into policies, rules and operations

Around 100 participants from Europe attended the research workshop “Climate change and the role of air traffic control” co-organized by Baltic FAB, FABEC and the German Aviation Research Society (GARS), hosted by the Vilnius Technical University in Lithuania. The event brought together high-level representatives of academic research institutes, air navigation service providers, regulators and other key stakeholders to discuss climate change and its impact on air traffic control (ATC) and, in parallel, ATC’s role in reducing aviation’s impact on global warming.

The event was opened by Virginijus Sinkevicius, European Commissioner for the Environment, Oceans and Fisheries, who underlined the Commission’s commitment to reaching the target of a climate neutral European Union by 2050. Then the results of new scientific research into aviation-related carbon dioxide (CO2) and non-CO2 emissions were outlined and discussed. Senior representatives from research agencies such as the German Aerospace Centre (DLR) and the Royal Netherlands Aerospace Centre (NLR), along with experts from Eurocontrol, Hungarocontrol, DFS and national governments who presented different stakeholder views on how to align scientific evidence with policies, regulations and operational procedures. Other imporant contributions came from representatives of the EC, PRB, economic and industrial think-tanks, academic institutes and consultancy companies.

It became clear from the discussions that new tools would be needed to more fully understand the impact of aircraft operations on greenhouse-gas formation and the most effective mitigation methods. New artificial intelligence and machine learning based analysis will give us a clearer picture of the impact of aviation operations on the environment – but the effectiveness of mitigation methods would depend on further research and all stakeholders working more closely together.

Key Messages

The workshop discussed the important interaction between climate change and aviation and considered in particular the role of air navigation services as an essential enabling infrastructure. It highlighted relevant findings of current scientific research into aviation-related Greenhouse Gas emissions and their expected impact. These facts were then seen in conjunction with political strategies and programmes e.g. the European Union's Green Deal and the European Commission's #Fitfor55 initiative as well as concrete operational experiences and goals of aviation stakeholders.

- The central focus of the European Commission's Environmental Strategy as it relates to aviation is the development of scalable, sustainable and advanced aviation fuels for predominant use in operations by 2050, and the optimisation of current technologies and procedures until then – with air traffic management playing a contributing role. Less emphasis seems to be placed on expected rebound effects

- Our scientific understanding of aviation-related environmental impacts is growing, but there are still high uncertainties over the impact of non-CO_2 emissions. Trade-offs between short-term and long-term effects of CO_2 versus non-CO_2 impacts are a subject of interest and to some extent controversy. There is a substantial lack of data and agreed metrics to drive further environmental improvements in a coherent and systematic way. While technological advances clearly reduce the footprint of individual flights, the historic growth of the number of aviation movements has overcompensated this by a large margin.

- The workshop, recognizing the urgency of mitigating action, supported the need to invest substantially into further research and data acquisition and to develop new metrics to quantify both performance and the potential for improvement. Stakeholders from science, technology and aviation will need to work more closely together, and continued EU support for applied R&D will be instrumental to achieve significant progress.

- The workshop participants expressed the willingness, competence and readiness of the ATM industry to support and further the Green Deal, but observed that a societal consensus, translated into clear policy directives, objectives and targets needs to be more clearly defined by the relevant bodies and authorities. Only a clear, common understanding of the meaning of "green flying" can form the basis for further progress towards a sustainable essential aviation sector.

- Experts warned against delaying concrete trials, tests and quasi-operational experiments and stated the urgency to act now instead of waiting for further scientific proof.

- There is a clear link between capacity, defined as a maximum number of flights passing through a sector, and environmental impact. A policy decision is required on whether to prioritise reducing emissions by limiting flight numbers or continuing to increase flight numbers but aiming for less environmentally damaging trajectories.

- Air navigation service providers require a legal framework setting unambiguous and clear priorities concerning different aspects of efficiency and environmental targets ranging from noise abatement, and air quality improvement to reducing climate impact.

- Recognizing the need to balance the sometimes-competing performance areas of safety, capacity, environment and cost efficiency, there is a need to adapt the current performance regulation to reflect that the implementation of Free Route Airspace has made the horizontal flight efficiency Key Performance Indicator obsolete.

- A total economic approach monetarizing all areas might be a suitable way forward – on the understanding that safety will never be compromised.

- To safeguard the European dimension, there is a need to provide the Network Manager with clear rules on how to manage the European network in an environmentally friendly way – to be laid down in the Network Managers Performance Plan.

- Some emerging impacts of climate change (e.g. intelligent use of changes to the location, orientation and strength of the jet stream may have a potential for some fuel savings) may help to reduce aircraft emissions while changes to e.g. convective events will lead to more disruptions.

- There is a need to improve the reliability and ease of access to real-time and cross-border weather predictions, including estimates of achievable accuracy.

- To reduce the impact of aircraft emissions on climate change a cross domain approach is required – incorporating policy makers, regulatory institutions, climate researchers, MET providers and all partners in the aviation value chain: airlines, aircraft and systems manufacturers, airports, the Network Manager and air navigation service providers.

As a general conclusion it was felt that while the participants all shared a sense of urgency in mitigating the negative impacts of climate change, and expressed their commitment to contribute to the success of such efforts, overall political guidance and leadership will be essential to achieve a fair, coordinated and successful effort across all sectors and stakeholders in aviation, which will continue to form an essential element of transport and mobility in the face of global challenges ranging from increasingly frequent and damaging natural disasters to pandemics.

Research Workshop

Climate change and the role of air traffic control

22-23 September 2021 in Vilnius, Lithuania

Conference venue: Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius

1st day – 22 September

Moderation: Prof Frank Fichert, Hochschule Worms; Roland Beran, FABEC Communication

9:30-10:30	**Registration and welcome**		
10:30-11:15	**Opening statements**	Virginijus Sinkevičius – *European Commissioner for the Environment, Oceans and Fisheries* Julius Skačkauskas – *Deputy Minister of Transport and Communications of the Republic of Lithuania* John Santurbano – *Vice-Chairman ASB/CEO Champion Environment, Director Maastricht UAC* Saulius Batavičius – *CEO Oro Navigacija* Prof Dr Habil Antanas Čenys – *Vilnius Gediminas Technical University (VILNIUS TECH)/Vice-Rector for Research and Innovation*	
11:15-12:00	**Keynote Speech: Climate change and its impact on air traffic control**	David Lee – *University of Manchester*	**page 15**

Lunch break

13:00-14:30	**Panel discussion 1: Effects of climate change on aviation (present and future)** *Moderator: Justas Kažys, Vilnius University*		
	ATC and environmentally friendly operations – Role and requirements	Heinz-Michael Kraft, Peter Oelsner, Ivar Mägi – *DFS Deutsche Flugsicherung*	**page 24**
	Adapting European ATM to a changing climate: Identifying the risks and quantifying the impacts	Rachel Burbidge – *Eurocontrol*	**page 32**
	Climate-induced meandering jet stream and its influence on air distance	Björn-Rüdiger Beckmann, Andreas Walter, Alexander Lau, Majed Swaid – *German Aerospace Center/DLR, German Meteorological Service/DWD*	**page 40**
15:00-16:30	**Panel discussion 2: Options for reducing CO_2 emissions** *Moderator: John Santurbano, Eurocontrol*		
	Real-time thunderstorm information enables fuel savings for long-haul flights	Caroline Forster, Alexander Lau, Benjamin Lührs, Andreas Petzold, Martin Gallagher, and Thomas Gerz – *WxFusion, German Aerospace Center/DLR, Technische Universität Hamburg, Forschungszentrum Jülich, University of Manchester*	**page 56**
	Mitigating the climate impact of non-CO_2 emissions: EUROCONTROL MUAC Live Trial 2021	Rüdiger Ehrmanntraut, Ilona Sitova, Kacper Walczak, Anja Burridge-Diesing, Milena Bowman, Nick Miller – *Eurocontrol*	**page 70**
	Multi-aircraft environmentally-scored weather-resilient optimised 4D-trajectories	Nick van den Dungen, Kinanthi Sutopo – *Royal Netherlands Aerospace Centre (NLR)*	**page 85**
16:30-16:45	**Wrap-up Day 1 and outlook**	Frank Fichert	

Social Event 19:00

Greeting and opening by Janusz Janiszewski, Acting President of PANSA (Baltic FAB)

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Research Workshop

Climate change and the role of air traffic control

22-23 September 2021 in Vilnius, Lithuania

Conference venue: Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius

2nd day – 23 September

9:00-9:15	**Starting the day**	Frank Fichert	
9:15-10:45	**Panel discussion 3: Reducing CO2 emissions – Interdependencies and potential trade-offs** *Moderator – Vidmantas Kairys, Vilnius Gediminas Technical University*		
	Toward novel environmental assessments for ANSPs using machine learning	Gabriel Jarry – *DSNA*	**page 96**
	Reducing Europe's impact on climate change using enriched air traffic forecasts and improved efficiency benchmarks	Hartmut Fricke, Markus Vogel, Thomas Standfuß – *Technische Universität Dresden, GfL Gesellschaft für Luftverkehrsforschung*	**page 116**
	Towards limited impact on environment	Jean-Michel Edard, Ilona Sitova – *FABEC, MUAC/Eurocontrol*	**page 136**
	Coffee break		
11:30-13:15	**Panel discussion 4: Holistic view on policy options** *Moderator: Frank Fichert, Hochschule Worms*		
	Economic estimates of the climate costs of the aviation sector due to air management: Insights for 2018 and 2019	Ibon Galarraga, Dr Herbert Pümpel, Luis Mª Abadie, Itziar Ruiz-Gauna, Nestor Goicoechea – *BC3, WMO, World Bank, Metroeconomica, University of Basque Country*	**page 150**
	An urgent need for a paradigm shift in policy making: ensuring sustainability and disaster mitigation in transport policies	Iván Arnold, Mira Bognár, Péter Székács, György Lovas and Vilmos Somosi – *Hungarocontrol*	**page 151**
	A holistic approach towards flight efficiency: maximising social welfare	Thijs Boonekamp, Bram Peerlings – *SEO Amsterdam Economics, Royal Netherlands Aerospace Centre/NLR*	**page 159**
	Lunch break		
14:15-15:15	**Final panel: Key messages on climate change and the role of air traffic control** *Moderator: Roland Beran*		
		Saulius Batavičius – *CEO Oro Navigacija* Marcel Zuckschwerdt – *Director General Civil Aviation Switzerland, FABEC* András Hujber – *European Commission* Magdalena Javorska – *Performance Review Body* Justas Nugaras – *Antanas Gustaitis' Aviation Institute*	
15:15-15:30	**Wrap-up of the workshop**	Frank Fichert	
15:30-15:40	**Closing remarks**	Saulius Batavičius – *CEO Oro Navigacija*	

Setting the Scene

Welcome Messages

Opening statement by Julius Skačkauskas,
Deputy Minister of Transport and Communications
of the Republic of Lithuania

The State must provide necessary leadership for operational improvements

Dear honourable guests, Welcome to Lithuania!

I believe that for many of the guests it is the first visit to our beautiful country, and to those who are visiting Lithuania after a while – welcome back! Visiting countries, meeting people, forming personal experiences and engaging in common initiatives is at the core of Europe's aviation community.

This event is already the 4th annual workshop arranged by functional airspace blocks and led by FABEC and the second one hosted by the Baltic FAB. By welcoming you all here in Lithuania, we are continuing the tradition of hosting each workshop in a different country.

Climate change and aviation is one of the most relevant and important topics today. As the Commissioner for the Environment, Mr Sinkevičius rightly emphasised in his welcome speech air transport in Europe not only is the driver of the economy but it also needs to play a key role in reaching Europe's goal: reducing noise and pollution levels and reaching climate neutrality by 2050.

We endorse the targets set in Destination 2050, the promotion of sustainable aviation fuels, improved ATM technologies and processes – all designed to reduce the environmental footprint of aviation.

The Ministry of Transport and Communications fully understands that all the players in the sector – airlines, airports, air navigation service providers, R&D organizations, just to name a few – need to play their roles to contribute to the common goal: sustainable air transport.

We recognise the importance of political support and the need for active participation on a State level in the implementation of the common tasks. It is the State and the regulatory bodies who must provide necessary leadership so that various operational improvements and decisions can be implemented.

Aviation strategy 2030 is one of the tools to encourage Lithuania's aviation sector to go green, that the Ministry of Transport and Communications is currently working on. By adopting this strategy at the end of 2021 Lithuania will have set its short-, mid- and long-term goals for the development of its aviation sector in a sustainable and environmentally friendly manner.

For us, the keyword is cooperation: both on the domestic level (with stakeholders in our country) and the international level (the Baltic FAB level, with all European Functional airspace blocks, and all other sectors all over Europe).

I am pleased to see academics, scientists, industry leaders, experts, practitioners and key policymakers at the same place and I sincerely believe that all the discussions during this workshop will take us at least one step closer to our goals.

**Opening statement by John Santurbano,
Vice-Chairman ASB/CEO Champion Environment,
Director Maastricht UAC**

A collaborative response

Friends, colleagues and guests,

Welcome to the beautiful city of Vilnius and what I believe to be one of the most important events of this year's air traffic management calendar.

It is wonderful we can all meet face to face, and many thanks indeed to our hosts for organising this meeting, to talk about a critical subject for everyone in this industry – and in society.

Actually, there are two critical subjects: the role that ATM will play in helping to reduce the impact of aviation emissions on the rate-of-change of global warming and the impact that global warming will have – is having – on our industry.

I want to preface my remarks by saying that I believe the scientific evidence of human activity's impact on climate change is irrefutable. The climate is changing and we are heading towards a point of no return, beyond which we will see a chain reaction start to form ever more volatile and intense weather events.

Civil aviation has always been essential for society, connecting people and transporting essential goods that contribute to improving our health and lives (as we saw last year).

Innovation is and will always be our industry's DNA. Improvements made in the last six decades have already massively reduced emissions and noise.

Today, we are going even further and faster. For example, with the introduction of free route airspace, we are close to the optimum level of horizontal flight efficiency.

Also, if we take a look at our radars, their energy consumption has been divided by 100 when we started using secondary radars after primary radars. And with satellites, energy consumption – hence emissions – have been even more reduced albeit service quality is improved.

These are just two examples. There are many more.

We will continue to innovate and improve. My colleagues in FABEC are united in their commitment to the European Union’s Green Deal environmental objectives and the acceleration of initiatives to reduce our carbon footprint and achieve our target of a net zero carbon emitting industry by 2050. Together, we will come out even better and stronger to face the challenges that are ahead of us.

During this workshop, we will be looking at promising initiatives and research to achieve our goals.

While we have a strong understanding about the amount and impact of CO2 emissions in aviation we know considerably less about the amount and impact of non-CO2 effects like water vapour, nitrogen oxide and carbon monoxide.

Without this detailed information we cannot start to understand how best to balance priorities and manage trade-offs. We will need to better understand not just how to balance improvements across all environmental areas but also environmental improvements against other performance domains, such as cost-efficiency and punctuality. We will, of course, always make safety our number one priority, but should aviation slow traffic down to lower emission rates? Should aviation prioritise environmental protection over cost-efficiency? The answer, of course, is that we cannot take these decisions by ourselves – as aviation industry. What and that whatever will be agreed it must be a collaborative response.

These will not be easy discussions but they are vital if we are to make the kind of progress across the industry which society quite rightly demands.

And that is why meetings such as this today are so important. More research and data analysis is required to provide a better basis for improving our environmental performance. We now have far more sophisticated data analysis tools than were available even five years ago, so we can now look at our performance in more detail and add new metrics to generate a more holistic, accurate view of our sector’s contribution. But it is still a long way to go. But – and this also clear – we have to take first steps.

So thank you for your commitment to be here today and the work you are doing. Your work is of extraordinary importance to the future of our industry and the wider world. And we as FABEC air navigation service providers take your contributions seriously and will translate them in our operations – providing an infrastructure which enables aircrafts to reduce emissions.

Thank you and I am very happy to follow the discussion.

Opening statement by Saulius Batavičius,
CEO Oro Navigacija

The focus on environment and sustainability is a must

Dear Commissioner, Vice-Minister, executive directors, honourable guests, colleagues and participants, it is a great honour and pleasure for me to be one of the hosts of this event, on behalf of Baltic FAB, and to greet you in this Vilnius TECH building, where numerous transport research and development (R&D) initiatives and innovations are born.

I would like to thank you all for the interest and attendance, especially bearing in mind the complicated times and gradual recovery from the pandemic. We estimated more than 130 attendees were registered, which proves that the subject of the conference – climate change and aviation – is a relevant topic, actually one of the most significant. We also understand and regret that some of the registered people could not attend because of the numerous restrictions still in place.

As it was already mentioned in other speeches, it is undeniable that air transport does impact the climate change, even if the role of different stakeholders of the aviation sector is not equal.

For instance, the goal of air traffic management is to ensure air traffic safety and guarantee efficient operations of the airspace users. When considering the role of air traffic control in climate change, the first thing that comes to mind is usually the ability of the air navigation service providers to indicate the optimal routes, which is clearly reflected in the performance scheme and the set KPIs. Besides horizontal flight efficiency, of course, there are other important aspects such as vertical efficiency, terminal holdings, taxiing time efficiency, noise levels, local air quality and so on.

To reduce the impact, air navigation service providers (ANSPs) implement various operational improvements, including optimised airspace structure, free routes, departure/arrival procedures, efficient use of airspace considering the demand of different users (including military ones), tactical support during the flight, noise reduction measures (together with airports, of course) and many other ways.

The problem is that nowadays the focus on environment and sustainability is no longer a nice-to-have matter, but rather a must, it is a prerequisite for any ANSP. Moreover, it requires appropriate infrastructure, data management, proper information flow to enable both planning and tactical actions when needed. Furthermore, it is no less important to keep an eye on R&D activities and innovation, which is why both Baltic FAB ANSPs – Oro Navigacija and PANSA – are actively involved in SESAR projects focusing on environmental improvements.

But at the same time it is not surprising that not only air transport affects the climate, but climate change also affects air transport in turn. With increasing number of natural disasters, it is a challenge to both ensure effective flight time and routes, while forecasting. According to statistics provided by our partners – Lithuanian Hydrometeorological Service – there is a new trend, i.e. a 12 percent growth of weather events, which are considered dangerous for air traffic. Thus, this fact cannot be ignored.

Vice-minister mentioned the first academic conference organised by functional airspace blocks on volatility of air traffic. During that conference and also beyond it, it was recognised that weather events and climate change in general are among the biggest factors of volatility. Thus, due to the interdependency we see that it is a circle.

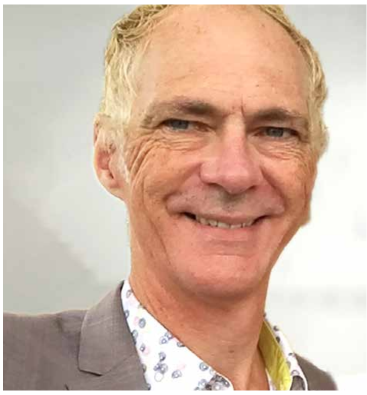
Last, but most certainly not least, both volatility and the ability of ANSP to ensure efficient flights is sometimes affected by political factors. Several years ago, traffic flows and routes in our region were greatly affected by the political conflict in Ukraine. This year, since the 27th of May, the flows and routes are impacted by the restrictions to use the Belarussian airspace. Unfortunately, currently the flight routes are far from optimal and subsequently have negative impact upon the climate.

To conclude, I would like to encourage you all to think of ourselves as one joint aviation community, to face the challenges together and to make Single European Sky blue (or green within the context of this conference), to think global and to remember that even small steps count.

I wish you a very productive conference! I will be available for any discussions during the next two days as well as for informal conversations during the social event!
improved.

Setting the Scene

Q&A with keynote speaker Prof David Lee



Setting the scene for the presentations that follow in this publication, Professor David Lee, Atmospheric Science Professor at Manchester Metropolitan University, provides answers to key issues concerning aviation and climate change.

What is the impact of aviation on climate change?

2018 is seen as a watershed year. For the first time, annual emissions of carbon dioxide (CO_2) attributed to aviation reached 1,000 million tonnes based on data from the International Energy Agency (IEA) and statistics from the International Air Transport Association (IATA). This is equivalent to about 2.5% of global annual CO_2 emissions for all sources.

Measurements going back as far as 1940 show that aviation has emitted a cumulative 32.6 billion tonnes of CO_2, of which more than half has occurred in just the last 20 years. Since CO_2 emissions accumulate in the atmosphere, it is the cumulative amount emitted that is important.

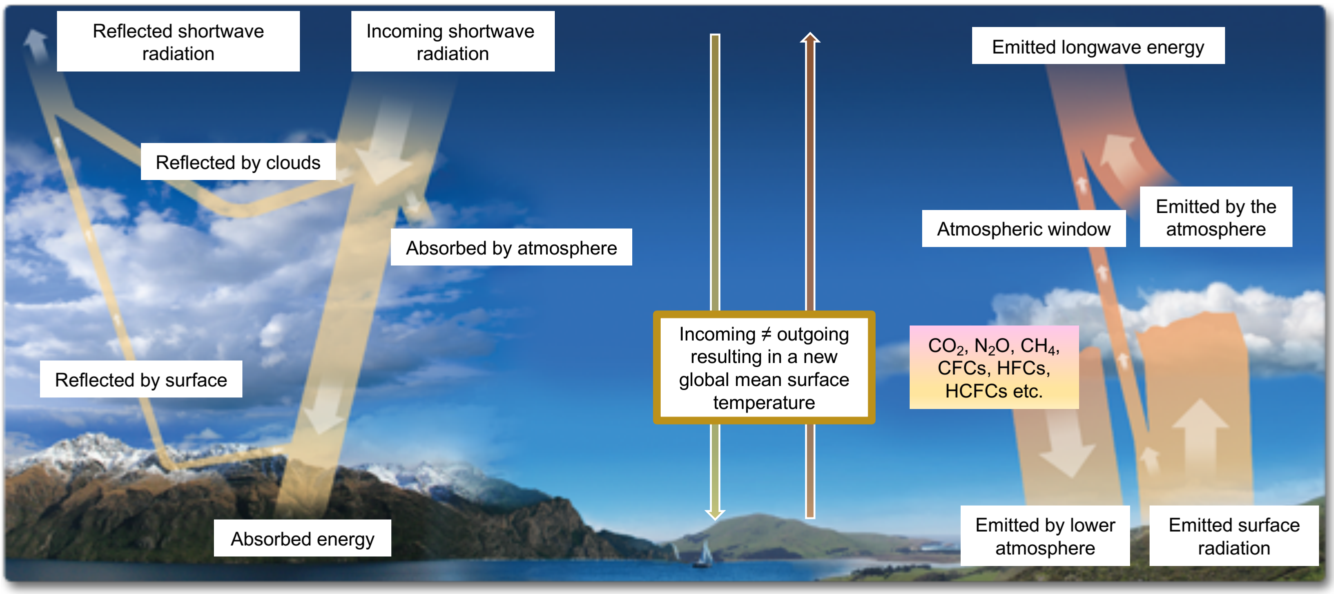
CO_2 is the principal greenhouse gas emitted by aviation, however there are also important non-CO_2 effects that also cause global warming. To calculate the impact of non-CO_2 emissions, a metric called Effective Radiative Forcing (ERF) is used that produces a positive number when the effect is warming, and a negative result if the effect is cooling. Currently, non-CO_2 effects represent about 66% of ERF attributed to aviation. When measured cumulatively, the CO_2 emissions result in about 34% of the total forcing and do not follow a linear pattern but vary with traffic volume.

What are the main causes of aviation radiative forcing?

The major radiative forcing terms include CO_2, contrail cirrus clouds (ice crystals that form behind an aircraft) and nitrous oxides (NOx). There are also minor contributions from water vapour, soot particles and interactions with sulphur aerosols. In total, the forcing attributed to CO_2 and non-CO_2 emissions from aviation amounts to about 3.5% of total anthropogenic forcing. However, the non-CO_2 effects are more uncertain and contribute eight times more than CO_2 to the uncertainties of net global aviation ERF.

If you insert powerful greenhouse gases like CO_2, NOx, methane and some of the fluorinated gases from refrigeration into the atmosphere, you upset the radiative balance of the atmosphere. In its natural state, the atmosphere reaches a balanced equilibrium between the short-wave solar radiation coming from the sun, and longer wave and infrared terrestrial radiation emitted from the ground. Some of the radiation is either reflected or absorbed by the clouds, but essentially this equilibrium global mean surface temperature makes the earth habitable.

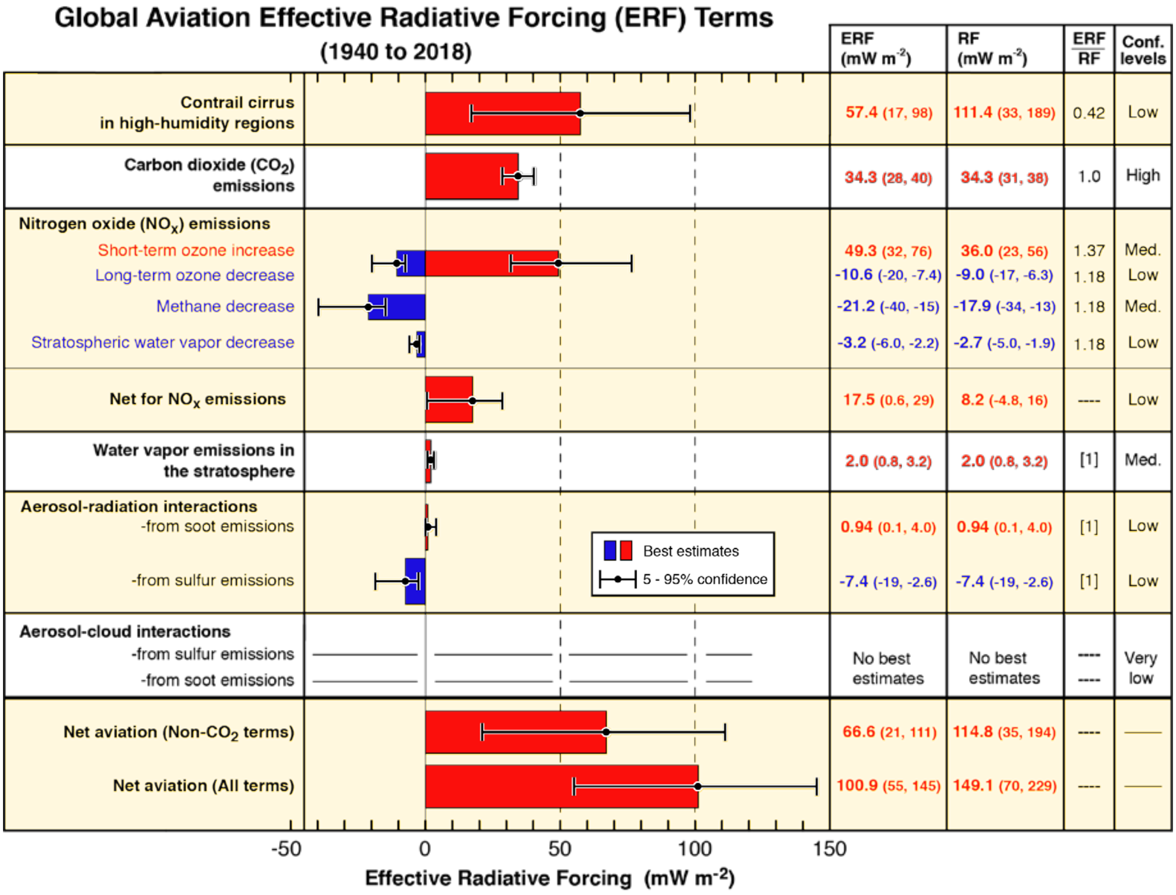
Forcing caused by emissions is measured in watts per square metre and has been traced and modelled from the pre-industrial age to the present day. It has a roughly linear relationship with global mean surface temperature change and shows that we are shifting the earth's atmosphere out of balance to reach a new equilibrium temperature. Improved computing power has enabled us to measure effective forcing in more detail.



Why is CO_2 so important?

A commonly held view is that CO_2 lasts about 100 years. In reality, it has several different lifetimes because it behaves in a complicated way in the environment. About half is removed within 30 years, and a further 30% within a few centuries. But the remaining 20% stays in atmosphere for thousands of years. This is the problem.

The largest contributor of aviation's non-CO_2 effects is from the formation of contrail cirrus in cold, high-humidity (strictly, ice-supersaturated) regions of the atmosphere. This is shown in the top bar of ERF chart below and accounts for close to 60 milliWatts per square metre (mW m2) ERF. CO_2 is the next most important, accounting for 35 mW m2. NOx emissions follow after this, although this produces both warming and cooling effects. NOx emissions result in a number of changes in the composition of the atmosphere, driven by chemical reactions, some of which are quite fast, some of which are quite slow. The net outcome is about 20 mW m^2 ERF. Total non-CO_2 ERF is calculated as 67 mW m^2 compared with aviation's total ERF contribution of 100 mW m^2.



	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions				
-from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
-from sulfur emissions	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

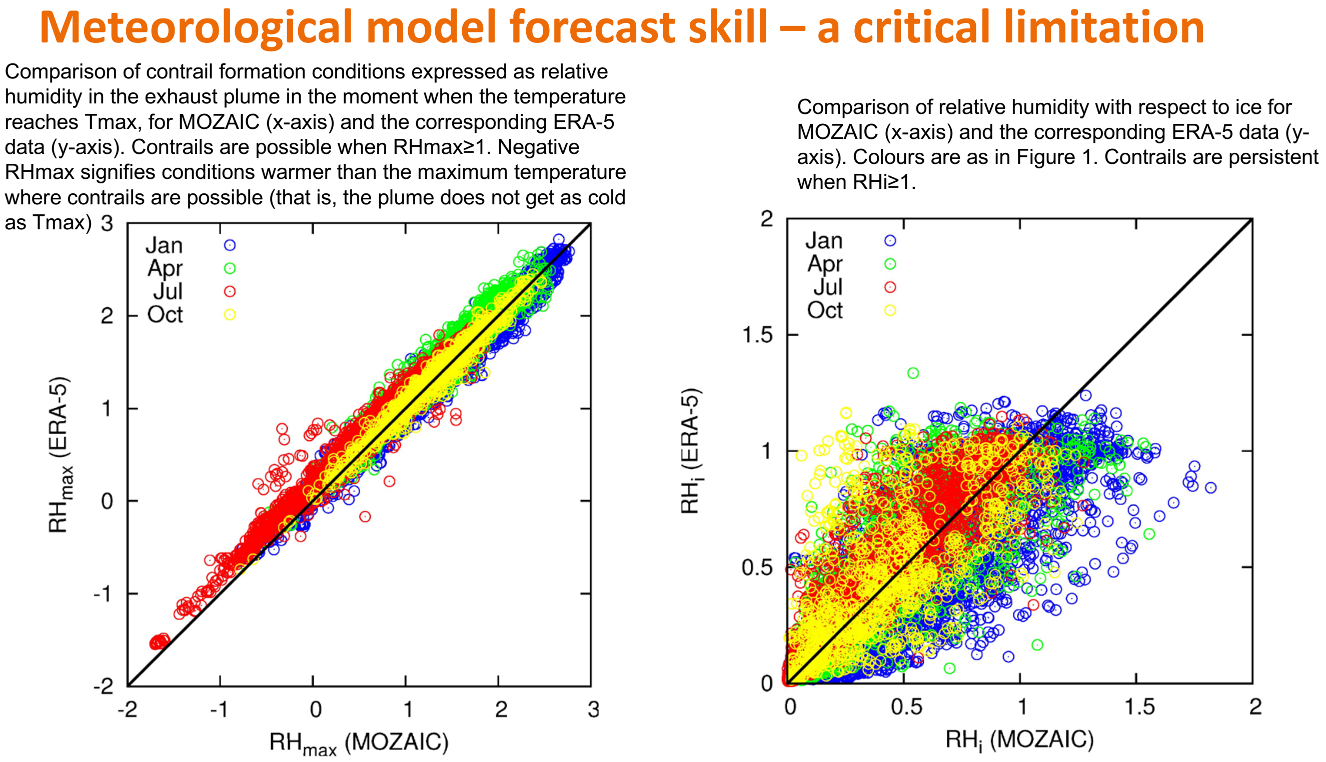
Source: Lee et al. (2020) *Atmospheric Environment*

How do you measure uncertainty associated with non-CO_2 effects?

The International Panel on Climate Change (IPCC) provides the methodology we use to assess results from ERF studies, modelling exercises and simulations. While the effect of CO2 emissions is relatively well known, non-CO_2 effects reveal very wide bands of uncertainty, which can vary by as much as eight times that of CO_2 as I mentioned earlier. To measure these parameters, we use Monte Carlo analysis methods to run multiple models with multiple variables to enable us to normalise the statistics and make assessments based on expert judgement. We do not always have as much data as we would like.

For net the NOx term, the level of uncertainty produces a range of results stretching from nearly zero to 29 mW m^2. We are not just comparing published numbers, these are carefully normalised statistics, and we obtain a good statistical spread from these. Essentially, NOx makes ozone (warming) and destroys methane (cooling).

Contrails are the white ice-crystal clouds that form behind an aircraft. Contrails only form when the atmosphere is humid (ice supersaturated) enough, and cold enough, to sustain them; and they may dissipate quickly or can become persistent, spreading into contrail cirrus. Most of the water content in the contrail cirrus comes from the atmosphere rather than the aircraft engine (which emits soot particles that trigger the initial contrail) and enables the background atmosphere to sustain them. Over tens of minutes to hours, contrail cirrus can spread out into a cloud. During the day, this reflects solar radiation back to space. It also reflects infrared radiation back down at night. So, there is a cooling and a warming effect, but the net effect is warming. We have difficulties predicting this.



Meteorological model forecast skill – a critical limitation

Comparison of contrail formation conditions expressed as relative humidity in the exhaust plume in the moment when the temperature reaches Tmax, for MOZAIC (x-axis) and the corresponding ERA-5 data (y-axis). Contrails are possible when RHmax≥1. Negative RHmax signifies conditions warmer than the maximum temperature where contrails are possible (that is, the plume does not get as cold as Tmax)

Comparison of relative humidity with respect to ice for MOZAIC (x-axis) and the corresponding ERA-5 data (y-axis). Colours are as in Figure 1. Contrails are persistent when RHi≥1.

Will sustainable aviation fuels help to reduce non-CO_2 effects?

Biofuels and synthetic aviation fuels (SAF) not based on gasification of fossil fuels offer a win-win for reducing climate change. Conventional kerosene contains aromatic compounds or impurities (such naphthalene) which are responsible for the formation of soot particles. These are tiny particles less than 10 nanometres in diameter, which the water vapour in the initial plume can condense on and subsequently freeze, with water vapour from the background depositing on them and forming larger ice crystals.

Biofuel and synthetic fuels tend to have zero aromatics in them. We know, if you reduce aromatic content, you reduce soot number concentration (which is more important than the mass emitted). This reduces ice crystal number concentration. The German research agency DLR published the first measurements showing this in early 2021 after observing the formation of fewer ice crystals behind an aircraft using clean SAF fuels. Further modelling will tell us how much this can reduce the forcing.

How can air traffic management help to reduce non-CO_2 effects?

A potential option is to fly around areas where contrail cirrus is likely to form. However, this is not straightforward as the sensitivity of the atmosphere varies regionally and is highly heterogeneous both physically and chemically. It is also sensitive to other emissions like NOx.

NOx effects do not occur in isolation. NOx changes the chemistry of the atmosphere, so it matters what else is going on due to highly coupled chemical reactions. The same aircraft emissions can have different effects depending upon the atmospheric conditions. In terms of airspace management, there are other trade-offs too, as taking longer routes or flying lower can result in increased CO_2 emissions.

Furthermore, comparing these trade-offs is not straightforward. There are a number of ‘emission equivalence’ metrics (e.g. the Global Warming Potential, GWP; Global Temperature change Potential, GTP, and others), they differ in their formulation, and the equivalence depends upon what time horizon you choose. You have to make a subjective choice over what is most important. The equivalence number changes with the time horizon.

One of the problems we have, we cannot, at present, predict persistent contrails with sufficient accuracy with meteorological models.

DLR has compared observations made in the real atmosphere using in-flight research aircraft and compared these results with modelled data. The formation of short-lived contrails is easy to predict as these are almost entirely based on thermodynamics. Persistent contrail formation is more challenging to predict however, and the research reveals that meteorological models are not able to predict with sufficient accuracy in time and space where contrail cirrus will form.

As a consequence, re-routing a flight could result in additional CO_2 emissions without reducing non-CO2 effects if contrail formation does not take place as predicted. On the other hand, contrail formation could be reduced, but CO_2 might increase to a greater extent. How do you calculate what is a good outcome, over what time scale and what distance? This is an important debate. Eurocontrol Maastricht Upper Area Control (MUAC) centre launched night-time trials in 2021 to introduce more real-flight analysis to the discussion.

European air navigation service providers face the additional challenge of managing complex, busy airspace which reduces the opportunity to reroute flights. Under existing policy, airspace management aims to minimise fuel burn and help airspace users travel from A to B as quickly as possible. Proposing alternative routes may not deliver on these existing objectives.

While the North Atlantic airspace has potential to support alternative routings, there are still many unknowns. Let's assume we can create sufficiently reliable meteorological models to predict the likelihood of contrail cirrus formation. You still need to know what the climate benefit might be, and if rerouting will generate more CO_2. For example, you can calculate an emission-equivalence using different metrics and different time horizons for CO_2 and contrail cirrus, but these values will vary between 1.7 and 39 depending upon the metric and time horizon chosen. Both answers are correct. These are complex questions which also impact policy.

What are your take-aways from these findings?

My personal advice is to always strive to reduce CO_2. We have high scientific confidence in the effects of CO_2, and reducing it has positive outcome.

At the same time, I'd be cautious of any actions that reduce non-CO_2 and increase CO_2 in a 'trade' situation for all the reasons given above. These decisions are associated with large scientific uncertainties and little certainty concerning the consequence, or size of any benefits compared with CO_2 emissions.

Undoubtedly there remains overall strong potential for reducing aviation climate effects. I have highlighted the issues from a scientific point of view, and I don't want to sound negative. In terms of the scientific agreement as to the readiness of air traffic management navigational avoidance of climate sensitive areas in terms of chemistry, or in terms of contrail formation, I'd say agreement on this, and how we do it, is "low".

Session 1

Effects of climate change on aviation

ATC and environmentally friendly operations – Role and requirements

Steffen Liebig, Ivar Mägi, Jessica Schicht, Peter Oelsner, Heinz-Michael Kraft[a]

Foreword

This document addresses mainly organisations and individuals who are not so familiar with air traffic control being part of air navigation service provision.

Since air traffic control started, its role focussed on managing safe air traffic operation. Performance aspects and first environmental requirements were added later due to increasing traffic demand and growing noise impact in the vicinity of airports.

With global warming and air traffic industry contributing to its development, a new challenge and task has been added to our working environment. Air Navigation Service Providers (ANSP), being a vital part of this industry are going to take their share in this challenging task.

During past 70 years global air traffic has gone through various learning and development processes governed or accompanied by the development of rules, standards, procedures and technologies. Our industry was always able to find solutions for the challenges it faced during those many decades. The technologies and procedures applied today are the result of those challenges and from the increasing demand of the past.

Along this long-lasting track many improvements were achieved but also set-back had to be digested. Nevertheless, there never has been another option than to continue.

Our industry is global. It connects continents with each other. It brings people together and transfers goods. There are not so many other industries who have this global background.

Global warming is a threat which cannot be addressed by local or regional solutions only. It needs at least a regional or even better global approach. And this is what our industry is used to do.

The ‘normal’ challenge – Volume and complexity

Since far more than a decade research how air traffic is contributing to global warming is ongoing. Even though the share of CO2 emission and other greenhouse gases caused by air traffic overall is relatively small, its impact together with contrail development is remarkable and in no way neglectable.

As knowledge and awareness grew, as well the search for solutions how to make flying more environmentally friendly started to develop and some progress today becomes more and more visible.

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[a] *all authors of DFS*

Research and development addresses potential measures and tools how to reduce green¬house gas emissions by alternative fuels, different propulsion concepts etc. or how to reduce contrail development to avoid the development of long-lasting cirrus clouds. Aside technical solutions (green fuel, light-weight materials, better aerodynamics etc.) operational approaches like vertical and horizontal flight efficiency etc. are expected to become part of the future toolbox to achieve the targets of "Green Flying".

However, another action area needs to be kept on focus at the same time, to allow the successful transfer of R&D results into daily business – traffic volume and complexity. Particularly when addressing operational solutions, this aspect becomes relevant.

In 2019, the year before the pandemic, about 3.334 million flights operated within German Airspace with more than 11,000 flights on peak day. At the same time Horizontal Flight Efficiency (HFE) already reached 98.8%.

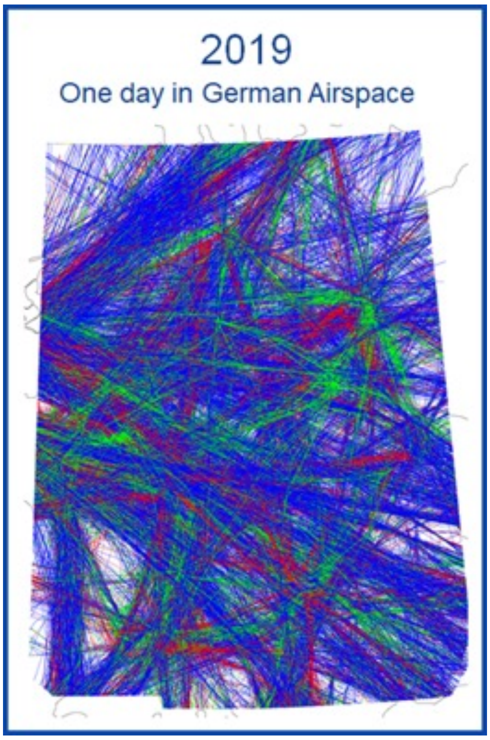


Figure 1: Flight tracks in German airspace – one day in 2019

Figure 1 shows the complexity and traffic density of just one traffic day in German airspace in 2019. Red colour shows departures, green colour is for arrivals and blue for over flights and level flights.

It must be considered that future "Green Flying Procedures" need to cope with similar amount of traffic volumes, traffic densities and structures. Operational management in such scenario will require clear rules and regulations to solve potentially conflicting requests.

Environmental and sustainable ATS – A demanding task

From historical perspective the original task of Air Navigation Service Providers (ANSP) was – and still is – to ensure a safe and orderly flow of air traffic. It is a service dedicated to airspace users operating in controlled airspace from take-off until landing.

Since the early beginning of ICAO in 1947, sets of internationally accepted standards, rules and regulations were developed for and applied by members of air traffic industry to support the maximum level of safety while economically operating air transport services.

To perform the operational services the ANSP applies a set of tools and complex infrastructure. Key elements are those ICAO rules but as well regional or national standards, rules and regulations. They form the base and framework of all activities and developments in our industry.

For proper operational planning and to take the right decisions and measures during day-to-day service additionally reliable up-to-date operational information and forecasts (e.g. weather, traffic volumes etc.) are needed and applied.

The ANSPs need to handle the traffic volume generated by the airspace user. The decision how many flights are generated, what type of aircraft, origin and destination of flight and time of flight is not with the ANSP but with the operator of the aircraft.

Since the early 70s requirements of noise abatement were added to the scope of tasks to be covered by air traffic industry. Aside the already existing rules, standards and regulations the aspect of noise abatement was implemented by a set new documents growing in number through the years and addressing the frame of requirements (e.g. ICAO Annex 16 Vol. I; ICAO DOC 8168 Vol. III – Section 9; 9501 Vol. I; 9829; 9888; 9943; 9993 etc.).

Those documents address the scope of aspects regarding noise certification, noise measure-ment and noise abatement procedures giving reliable guidance to members of air traffic industry.

Aside the ICAO documents outlining the common rules and regulations as well regional and even sometimes local requirements on noise abatement measures and regulations are in place which need to be considered during operation.

Regarding CO_2 emission relatively few documents describing rules and standards have been issued so far in recent years. However, they primarily focus on aircraft and engine certification and CO2 emission measurements (e.g. ICAO Annex 16 Vol. II, III and IV; ICAO DOC 9501 Vol. II, III, IV).

To summarize – regarding the requirements for safe and orderly flow of air traffic as well as for noise abatement proper guidance material, rules, standards and regulations are in place addressing the role and needs of ANSP.

Answering the question how to perform an environmentally friendly ANSP service there is none yet. Particularly addressing the questions how to handle conflicting goal settings like

- CO_2 reduction vs. contrail avoidance
- CO_2 reduction vs. noise abatement around airports or
- CO_2 reduction / contrail avoidance vs. economical flight profiles

are not addressed until today. However, air traffic industry needs a clear picture and guidance on this.

Environmental and sustainable ATS – Prerequisites for ANSP

Rules, Tools and Information (RTI) are the three elements based on which ANSP perform their services. In context with environmentally friendly ATS operation it is clear to ANSP that reducing greenhouse gas emissions and the avoidance of contrails are the keys to success.

Addressing the handling of individual flight trajectories within a given traffic scenario and weather conditions is daily business for ANSPs and Air Traffic Control. The basic instruments for air traffic controller performing their tasks are related to give clearances for speeds, flight levels, take-off and landing, climb and descent profiles and directions and to receive and provide relevant information to give the correct clearance at the right time. Those instruments will be the very same for managing and handling environmentally friendly ATS.

Challenges are with potentially conflicting goal settings which need to be managed and organised by a set of proper rules and regulations and the provision of adequate and up-to-date information needed to identify the correct measure and its timing to reach the goal.

Today, within the area of responsibility of DFS (Deutsche Flugsicherung) GmbH there is a clear set of rules addressing the operational performance of air traffic services and for the management of noise abatement procedures in the vicinity of airports. Large efforts have been undertaken during the past decades to arrange noise abatement procedures together with the original tasks of Air Traffic Services. In many cases noise abatement procedures are linked to e.g. departure routes bypassing inhabited areas, causing additional flight mileage leading to higher fuel consumption and therefor also producing higher CO_2 emission.

How will this be in the future? Will there be priority of CO_2 reduction on noise abatement in the vicinity of airports or vice versa? Priority of avoiding contrails by bypassing dedicated airspace areas or to minimize CO_2 emission going directly through those areas? Under which conditions prevails one the other? Where is the break-even point to decide which is the best way forward to achieve an environmentally friendly flight?

Aside the in-depth knowledge on how to deal with individual flights to reduce greenhouse gas affecting climate it is of same importance to identify and define what is the most environmentally friendly way forward and to transfer this knowledge into day-to-day operational situation.

To provide a single flight with an environmentally friendly flight trajectory is one aspect. To provide a larger number of flights with environmentally friendly flight trajectories within a dedicated volume of airspace is much different. Particularly if the individual optimum flight trajectory differs from aircraft to aircraft.

Proper rules and regulations how to act – particularly in case of conflicting goal settings – is one major prerequisite needed by ANSPs to operate an environmentally friendly ATS.

Adequate tools enabling the operational management of such situation and reliable forecast and up-to-date information allowing the take the right decision under given conditions are the other two vital elements which need to be established in this context.

The “Alpine Weather Procedures” established between four ANSPs gives an example how it may work.

Learning from ‘Day-to-day’ OPS – ‘Alpine Weather Procedures’

For some years an increase of adverse weather conditions combined with severe thunder-storms could be observed in the Alpes region. They are often accompanied by Cumulus clouds reaching extreme lateral and vertical dimensions. As well the average distances between the different cells tend to decrease.

Rules

The challenge of handling air traffic expected to heavily deviate from initial planned flight trajectories and / or flight levels and incorporating cross border areas led Skyguide, ENAV, Austrocontrol and DFS to agree on a common alpine weather procedure settled in a specific Letter of Agreement (LoA).
This LoA describes the commonly agreed process and procedure defined for three phases:

- ***Monitoring phase***
  Adverse weather conditions in one area of responsibility (AoR) indicate a high potential that initially agreed conditions for transfer of control are going to be affected in case aircraft need to deviate. The unit responsible for this AoR initiates a conference call incorporating all neighboring units potentially affected. This call is used to exchange relevant status information. This phase represents an early “heads-up” information and raises situational awareness.
- ***Supporting phase***
  When first deviations occur another conference call should be initiated with the neighbouring units. The information exchange gives an update on status of situation and additionally information on tactical measures planned or taken together with next steps and timeline. This phase represents a kind of “stand-by” warning for the other units and the deviations to be followed or expected during the following deviating phase.
- ***Deviating phase***
  When deviations cross the common AoR into adjacent unit’s AoR, which initially was not planned for this flight the deviation phase is initiated to arrange proper coordination and information exchange.

All relevant details and information for those three phases and related processes are setup in a LoA document and – as such – form the set of rules which need to be followed.

Tools

The operational application of the Alpine Weather Procedures requires an early knowledge of the potential development of adverse weather condition. The tool used in this context is


Figure 2: LoA Alpine Weather Procedures (extract) [1]

the Cross Border Weather Forecast provided by the Network Manager / EUROCONTROL in Brussels. In different layers it provides weather information and forecast in graphical and textual form covering different time periods the day before (D-1) and on actual day (D.0) (Figure 3).

Information

The structure and layout including the matrix and color codes provide a quick and easy overview on upcoming weather phenomena (what – where – when) which is vital for proper pre-tactical (Day-1) and tactical planning (Day-0).

For pre-tactical planning information raised from Cross Border Convection Forecast can be considered for sector configuration, sector opening and/or closing times and shift rooster planning.

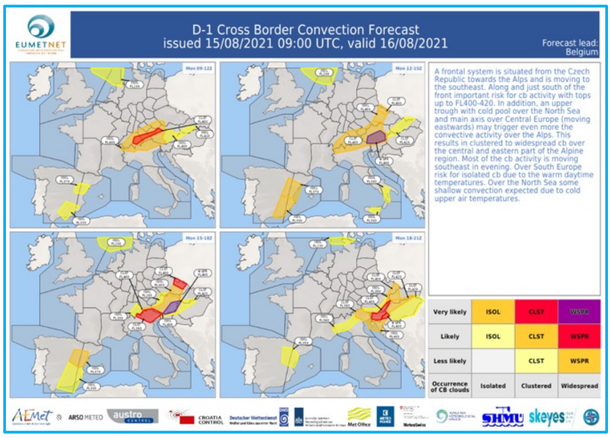
During day of operation and when need is given to react on short term development (2-3 hours from present) with e.g. changing sector configuration or sector opening / closing time, traffic regulation information is used for tactical planning.

What to learn from “Alpine Weather Procedures”?

The example shows how a potential working and process environment for handling avoidance of contrails may look like.

First: A set of agreed rules and regulations is required defining how to handle traffic situation in case deviations are needed or required or recommended to avoid contrail development. Such rules most likely should as well cover the potential conflict between CO2 emission reduction and contrail avoidance.

Second: A tool adequate to provide an area overview on when and where the potential “no-go” areas are located to avoid contrail development and how they are expected to develop. Pre-tactical and tactical planning must be enabled to allow ANSPs to prepare for developing and changing conditions well in time.



D-1 Cross Border Convection Forecast
issued 15/08/2021 09:00 UTC, valid 16/08/2021

Forecast lead: Belgium

A frontal system is situated from the Czech Republic towards the Alps and is moving to the southeast. Along and just south of the front important risk for cb activity with tops up to FL400-420. In addition, an upper trough with cold pool over the North Sea and main axis over Central Europe (moving eastwards) may trigger even more the convective activity over the Alps. This results in clustered to widespread cb over the central and eastern part of the Alpine region. Most of the cb activity is moving southeast in evening. Over South Europe risk for isolated cb due to the warm daytime temperatures. Over the North Sea some shallow convection expected due to cold upper air temperatures.

Figure 3: Cross Border Convection Forecast for 16.08., for four consecutive 3 hours-periods, issued 15.08. [2]

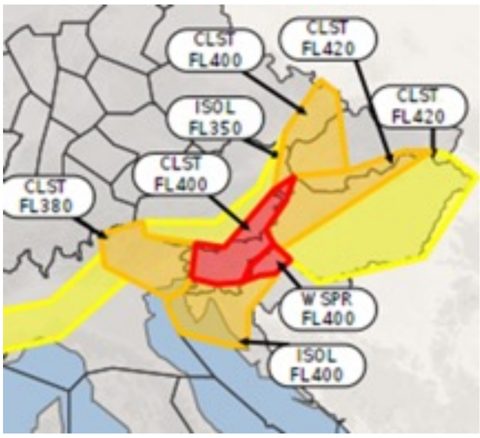
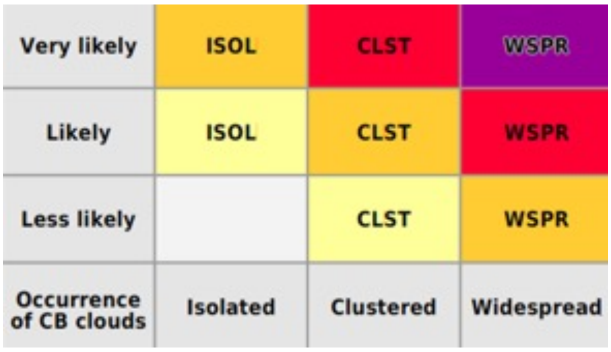


Figure 4: Flight Level Information on CBs [2]



Very likely	ISOL	CLST	WSPR
Likely	ISOL	CLST	WSPR
Less likely		CLST	WSPR
Occurrence of CB clouds	**Isolated**	**Clustered**	**Widespread**

Figure 5: Colour Code Matrix [2]

Third: The relevant information not only on the potential “no-go” areas and their extension but as well on traffic demand and other factors influencing the final process need to be provided at level of detail needed and early enough. The information will be the baseline for well trained and competent OPS personnel to identity and apply the adequate procedures.

Conclusions

Global warming most likely is the strongest threat air traffic industry has ever faced. There is no bypass. Our industry must enable environmentally friendly flight operation. Within its action areas ANSPs must undertake all reasonable efforts to achieve “Green Flying”.

Independently to this enormous challenge safety of each individual flight was, is and will always be ANSPs’ highest priority.

The operational competence how to handle flights is given with ANSPs. That is our daily business.
To handle flights in an environmentally friendly way ANSPs require clear guidance by

- clear and proper rules, standards and definitions how an environmentally friendly flight looks like,
- information about relevant aspects and conditions applicable to the individual traffic situation
- and appropriate tools and procedures

enabling ANSPs to transfer their competence into operational action.

Particularly when addressing conflicting goal settings e.g.

- avoidance of contrails vs. CO2 emission
- CO_2 emission vs. noise abatement
- “green flying” vs. capacity requirements

clear guidance is required to be successful.

And progress must be much faster compared to noise abatement activities during past 50 years. To stop global warming, we don’t have 50 years left.

ICAO Documentation listed

ICAO Annex 16 Environmental Protection
    Volume I – Aircraft Noise
    Volume II – Aircraft Engine Emissions
    Volume III – Aeroplane CO2 Emissions
    Volume IV – Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

DOC 8168 Aircraft Operations Vol III – Aircraft Operating Procedures – Section 9. Noise abatement procedures

DOC 9501 Environmental Technical Manual –
    Volume I – Procedures for the Noise Certification of Aircraft
    Volume II – Procedures for the Emissions Certification of Aircraft Engines
    Volume III – Procedures for the CO2 Emissions Certification of Aeroplanes
    Volume IV – Procedures for demonstrating compliance with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)
DOC 9829 Guidance on the Balanced Approach to Aircraft Noise Management
DOC 9888 Noise Abatement Procedures: Review of Research, Development and Implementation Projects Discussion of Survey Results
DOC 9943 Aircraft Noise Technology Review and Medium and Long Term Noise Reduction Goals
DOC 9993 Continuous Climb Operations (CCO) Manual

References

[1] LoA – Letter of Agreement between Karlsruhe UAC/ACC-FIC Vienna, page D7
[2] NM cross border weather forecast D-1 with the friendly support from Network Manager, EUROCONTROL Brussels and EuMetNet

Adapting European ATM to a changing climate: Identifying the risks and quantifying the impacts

Rachel Burbidge[a]

Abstract

Climate change is creating operational, infrastructure, business and safety risks for European aviation. Our sector needs to understand them so as to adapt and build resilience to potential future impacts such as more frequent and powerful heatwaves and storms. This paper presents results from a new study from EUROCONTROL, the European Organisation for the Safety of Air Navigation on two climate change impacts of most importance to European ATM: how will changes in frequency and intensity of storms impact delays and flight efficiency, and how will changes to en-route wind patterns impact flight times and fuel burn? The study finds that by 2050 overall delays due to major storms and summer convection may decrease. However, when there is a delay due to a major storm the delay will be greater than it is today. Changes to en-route wind patterns could decrease flight times, fuel burn and CO2 emissions on routes between Europe and North America, north Europe and Asia and north Europe and the Canary Islands by 2050.

Introduction

The latest analysis from the United Nations Intergovernmental Panel on Climate Change (UN IPCC) reports that earth's global average surface temperature is likely to reach 1.5°C above pre-industrial levels, the optimal target set out in the Paris Agreement, within the next 20 years, regardless of any actions taken to cut greenhouse gas emissions in that time. Therefore, due to historical and ongoing emissions, some future climate change is unavoidable, even if rapid action to reduce emissions is achieved (IPCC, 2021). Disruptive weather is already creating operational, infrastructure, business and safety risks for European air traffic management (ATM), and these are expected to increase as our climate changes. Our sector needs to understand these risks so as to adapt and build resilience to potential future impacts.

Although work has been done to identify the potential impacts of climate change for European aviation at a qualitative level, until now less has been done to actually quantify the impacts. A new study published in September 2021 by EUROCONTROL , the European Organisation for the Safety of Air Navigation, now provides this quantitative data (EUROCONTROL, 2021a; EURO¬CONTROL, 2021b). It presents analysis of European airports at risk of sea level rise, how changes in frequency and intensity of storms will impact delays and flight efficiency, how climate driven changes in tourism demand might impact traffic demand, and how changes to en-route wind patterns could impact flight times and fuel burn. This paper presents the results of the two elements of the study of most importance to European ATM: how will changes in frequency and intensity of storms impact delays and flight efficiency, and how will changes to en-route wind patterns impact flight times and fuel burn?

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[a] *EUROCONTROL.*

[1] *The analysis was commissioned by EUROCONTROL. The analysis was carried out under contract by Egis Aviation and the UK MET Office in coordination with the EUROCONTROL Aviation Sustainability Unit and Network Manager.*

Changes in storm patterns

Patterns in storm intensity and frequency were investigated for both historical (2010-2019) and future periods (out to 2050). Two types of storms were considered: convective storms which occur most frequently in the summer period, and windstorms which are more frequent in winter. Convective storms have the biggest impact in the south of Europe and windstorms in the north.

Potential changes in the impacts of storms on European air traffic were measured through identifying days on which they caused significant air traffic flow management (ATFM) delays termed Significant Weather Days (SWDs). Thresholds for causing impacts were then developed and used to quantify their probability of being exceeded, both on any given day and for days according to the type of weather pattern with which they are associated. This established a link between potential disruptive weather and a number of weather patterns. For example, weather patterns, which draw warm and humid air northward from the Mediterranean are associated with a greater probability of en-route ATFM delay due to convection. Whereas, weather patterns characterised by deep low-pressure systems across northern and southern Europe are associated with a greater probability of arrival ATFM delay due to high surface wind speeds.

A very strong relationship was found between the SWDs experiencing the most significant en-route ATFM delays and the occurrence of convective storms, for which country average Convective Available Potential Energy (CAPE) was used as a proxy. A clear increase was found in the likelihood of a SWD occurring on a day that sees a country average CAPE value of greater than 100 J/kg. For windstorms, the likelihood of a SWD occurring was higher on days where surface wind speeds at an airport were greater than 10 m/s. However, there is much variation across Europe and the number of days where these thresholds are exceeded varies considerably state by state. The CAPE threshold is exceeded most regularly in southern Europe while the wind speed threshold is exceeded most regularly in northern Europe, particularly its coastal areas.

Future changes in storm occurrence

Perhaps counterintuitively in a climate change context, the climate model projections out to 2050 identified a possible tendency towards more frequent occurrence of weather patterns which typically cause settled weather across the north of Europe. This suggests that disruptive convective activity may actually become less common, leading to fewer days with weather-related disruption.

However, using extreme daily rainfall as a proxy for convective activity, extreme rainfall days are projected to increase across northern Europe, whereas they are projected to decrease for southern Europe (Figure 1). However, the regions of northern Europe that are projected to have the greatest increase in days with extreme rainfall do not currently see frequent disruption due to convective activity. Therefore, the decrease in days with extreme rainfall across southern Europe, where there is currently the greatest potential for en-route ATFM delays due to current climatic conditions, is of relatively greater import-

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[2] *A measure of convective activity. CAPE integrates two key ingredients for deep and moist convection, instability and moisture. CAPE is measured in units of J/kg.*

ance for ATM. However, while major storms may become less common in this region there will still be extreme convective activity, and individual storms may be more powerful than they are today.

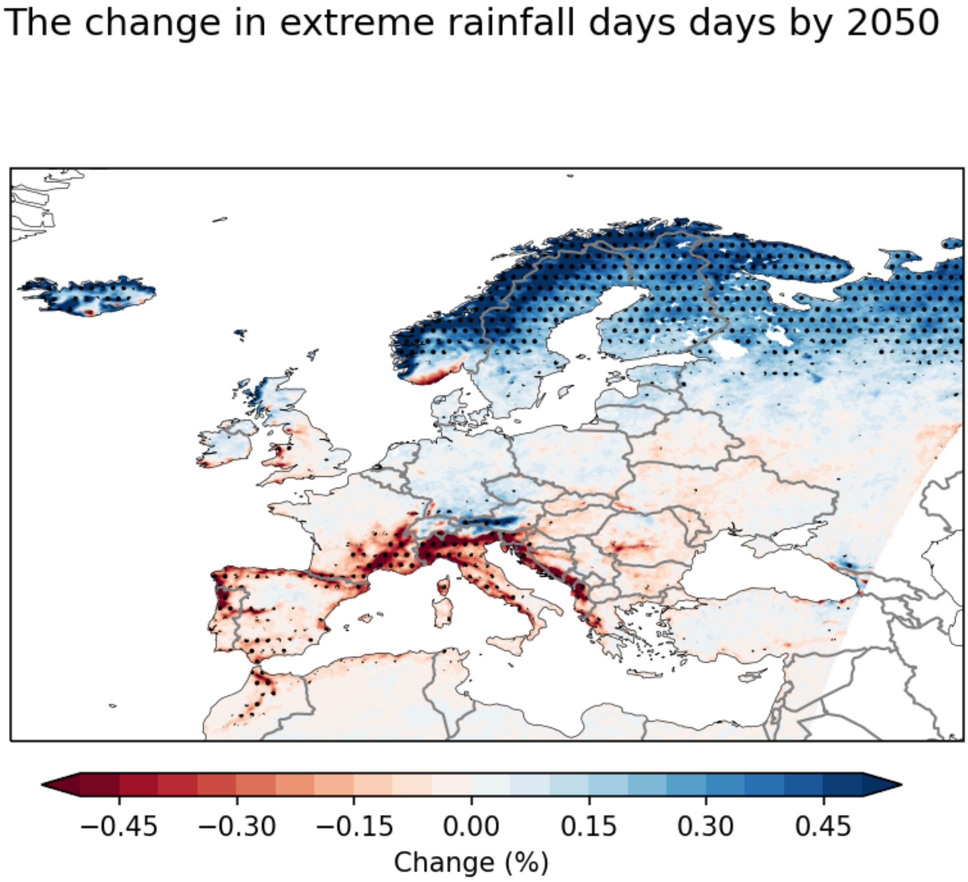


Figure 1: The percentage change in the number of days exceeding 26.2 mm of rainfall in summer (taken as April-September) for 2036-2065, relative to 1981-2010, for the RCM-PPE ensemble in the RCP8.5 emissions scenario. Black dots indicate where a robust change is simulated and the ensemble range (taking the second lowest and second highest projected changes from the ensemble to indicate the range) does not span zero change.

Current and future operational impacts of storms

The projected changes in weather patterns out to 2050 and EUROCONTROL operational data were then used to analyse how changes in potential disruptive weather may impact European aviation delays and flight efficiency in this time period using a set of operational metrics. Two possible traffic growth scenarios were considered as produced for the most recent Challenges of Growth forecast released in 2018, namely "Regulation and Growth" (Scenario A) and "Happy Localism" (Scenario, B) (EUROCONTROL, 2018). A third scenario (Scenario X) was introduced to eliminate the impact of uncertainties related to the aviation system in 2050. This is a theoretical scenario focussed on quantification of net

[3] *Regional Climate Model – Perturbed Physics Ensemble (RCM-PPE)*

[4] *Representative Concentration Pathways (RCPs) Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover (IPCC, 2014). RCP8.5 is the worst-case scenario.*

[5] *https://www.eurocontrol.int/publication/challenges-growth-2018 Regulation and Growth (Most-Likely): moderate growth regulated to reconcile demand with sustainability issues. Happy Localism: like Regulation and Growth, but with a fragile Europe increasingly, and contentedly, looking inwards.*

impacts of changing storm patterns while keeping all the other variables constant, including traffic levels.

Historically, storms are responsible for up to 7.5% of total en-route ATFM delays at network level. The average en-route ATFM delay due to weather per flight delayed by a major storm is currently estimated to be around 17-18 minutes per delayed flight (2019). Perhaps counterintuitively, by 2050 the total number of flights experiencing en-route ATFM delays due to a major storm is projected to decrease. However, if a flight is delayed by a storm, the delay is likely to be around 3-4 minutes longer than it is today, although there will be regional differences (Figure 2).

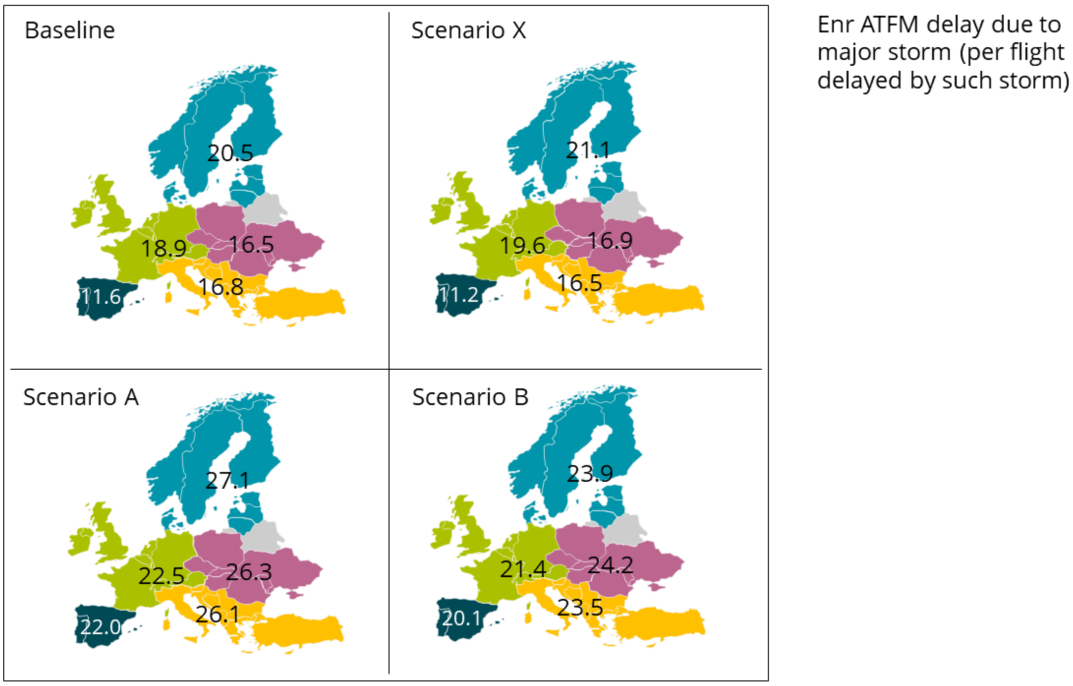


Figure 2: Average en-route ATFM delay due to weather (in minutes) per flight caused by a major storm projected in 2050 (2013-2019 baseline).

For safety and passenger comfort, flights usually try to avoid stormy areas. This causes additional distance to be flown in order to avoid the storm. Historically, the average horizontal flight inefficiency measured at network level during days of major storm activity was 20% worse than the annual average. In 2019, over 1 million additional kilometres were flown in order to avoid a major storm. This equates to around 6,170 tonnes of additional fuel consumed, or 19,430 tonnes of additional CO2 produced. However, except for a small number of localised storms that caused substantial increases in horizontal flight inefficiency, the horizontal flight inefficiency measured on days with major storms was rarely more than 4%. Due to the localised geographical extent of storms, the overall impact on annual performance remains small. The average horizontal flight inefficiency measured across all days when major storms accounted for at least 50% of en-route ATFM delays between 2013-2019 was 3.50% (3.59% in 2019). Given the anticipated changes in storm patterns by 2050, this figure is likely to increase to 4.0% - 4.2%. This is a notable increase from the 3.6% experienced during major storms in 2019. This should be considered in the context of the overall average horizontal flight inefficiency across 2013-2019, which ranged from 2.7%

to 2.9%. Based on 2019 air traffic, it is estimated that a flight will need on average 11.76 kg of extra fuel during a major storm to cover the average additional distance flown.

Vertical flight efficiency (VFE), measured as distance flown level during approach or climb phases of flight, was also analysed. As most storms occur during the peak traffic summer months (June, July, August) vertical flight efficiency was compared on days when major storms took place against typical vertical flight efficiency in those months. Notable variation in impacts was found for the states in the sample, with the general seasonal impact on vertical flight efficiency during the climb phase of flight being greater than the impact on vertical flight efficiency during the descent phase. However, due to the unavailability of future storm pattern projections for individual airports, it was unfortunately not possible to forecast potential future impacts.

Changes in Wind Patterns

Changes to high-altitude winds on flights to, from and within Europe could impact flight times and fuel burn. The day-to-day variability of high-altitude winds already has a considerable influence on the time-optimal routes of aircraft (i.e. the routes with the shortest flight times) and any projected changes in high-altitude winds could shorten or lengthen flight times, with corresponding impacts on fuel burn and CO2 emissions. Projected changes in weather patterns by 2050 were used to infer potential changes in flight duration for flights between Europe and North America, Europe and Asia and Europe and the Canary Islands by 2050.

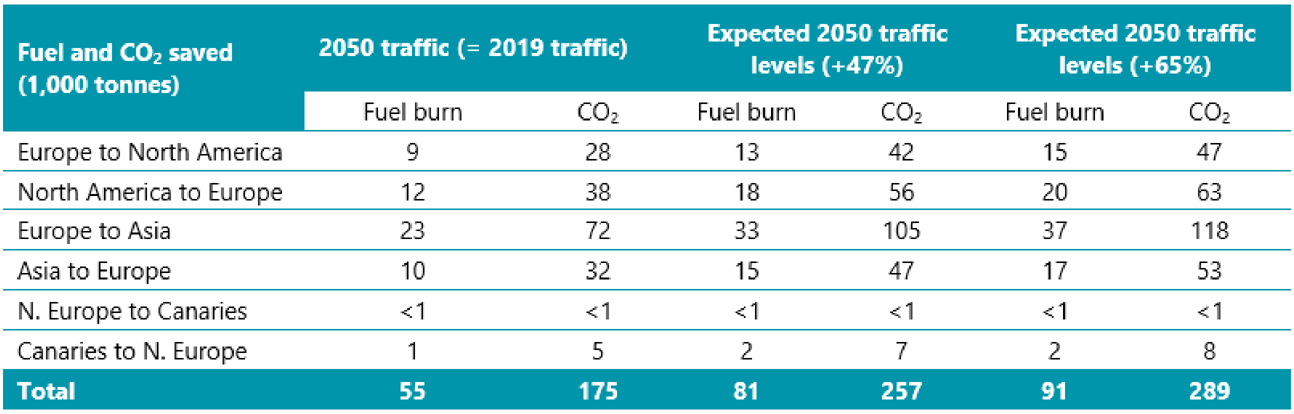
Historical flight times were calculated for every day in the 2010-2019 period as a reference, using a state-of-the-art trajectory prediction (TP) algorithm developed by the UK MET Office. The days were then categorised according to a set of eight typical weather patterns to establish any relationship between fast or slow days and specific weather patterns. Climate model projections for changes in the weather patterns were then used to infer potential changes in flight duration out to 2050. In addition, the TP algorithm was applied directly to historical and future climate model data, to calculate flight duration changes.

Projected changes in flight time by 2050

The results indicate that flight durations from the Canaries to North Europe (northbound) are projected to decrease in both summer and winter by approximately 1-3 minutes, while flight durations from North Europe to the Canaries (southbound) could decrease in summer by about 1 minute and increase in winter, also by about 1 minute. Flight durations are also projected to decrease for flights from Europe to Asia in both seasons, and for Asia to Europe in summer by approximately 2-5 minutes. Changes are most pronounced for flights between Europe and North America and between Europe and North Asia in the winter months when the jet stream tends to be strongest. For transatlantic routes, flight durations will decrease in both westbound and eastbound directions, for both summer and winter by approximately 1-2 minutes. For eastbound flights this is because of stronger tailwinds, whereas for westbound flights this is because, in the winter, the jet stream is narrower and therefore less of a detour is needed to fly around it. The differences in flight times are less obvious for flight between Europe and South Asia, and Europe and the Canaries. This is mainly because flights on these routes spend less time affected by the jet stream. Of course, savings of a few minutes are obviously small in the context of multi-hour flights, and also small relative to other potential time savings, such as removing the constraint of the current organised North Atlantic Track System (to be achieved through complete satellite-based ADS-B surveillance coverage). The results that have been achieved from the application of the TP algorithm to the climate model output contrast somewhat with those in recent academic literature. This is likely to be due to differences in the approach and method. The main difference with other work is the use of a different TP algorithm and the extension to considering a larger sample of climate models, but other subtle differences in the approaches may also explain the results. This suggests there would be value in further studies to build consensus and should not be interpreted as a definitive answer. However, it is a step in expanding our current knowledge and understanding.

Quantification of future operational impacts

Quantification of the future operational impacts of changing high-altitude winds on average flight duration, ground speed and fuel burn was then estimated based on a combination of the TP output and operational data from the EUROCONTROL R&D Archive. While the projected future changes in flight duration per flight are small the combined impact of all flights operating on the traffic flows considered in the analysis is more notable. The overall reduction in flight times, as a result of projected changes in high-altitude winds, is likely to decrease aviation fuel burn on the routes analysed by more than 55,000t per year, which corresponds to an approximate decrease of 175,000t of CO2 emissions per year, with the greatest reduction expected on routes to and from Asia (Table 1). However, these results assume current fleet mix, aircraft performance and pre-pandemic traffic levels. Traffic, fuel burn and emissions are forecast to increase substantially from 2019 to 2050. The fuel and emissions reductions due to changes to the jet stream on the traffic flows analysed should therefore also increase accordingly.



Fuel and CO_2 saved (1,000 tonnes)	**2050 traffic (= 2019 traffic)**		**Expected 2050 traffic levels (+47%)**		**Expected 2050 traffic levels (+65%)**	
	Fuel burn	CO_2	Fuel burn	CO_2	Fuel burn	CO_2
Europe to North America	9	28	13	42	15	47
North America to Europe	12	38	18	56	20	63
Europe to Asia	23	72	33	105	37	118
Asia to Europe	10	32	15	47	17	53
N. Europe to Canaries	<1	<1	<1	<1	<1	<1
Canaries to N. Europe	1	5	2	7	2	8
Total	**55**	**175**	**81**	**257**	**91**	**289**

Table 1: Fuel and emissions reductions from taking advantage of changes to the jet stream on the traffic flows analysed

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[6] *https://www.eurocontrol.int/dashboard/rnd-data-archive*

[7] *Minor inconsistencies in the fuel burn and CO2 values are due to the rounding of results.*

[8] *The European Civil Aviation Conference (ECAC) has 44 member states https://www.ecac-ceac.org/about-ecac/member-states*

Adapting to a changing climate

Overall, these results suggest that changes to our climate will bring both challenges and opportunities for European ATM out to 2050. The quantitative analysis provided by the study provides vital information for the future operation of the European ATM network and concrete data on which to base short to mid-term decision-making so as to minimise the potential risks of climate change for both individual organisations and the network as a whole. The results have shown that potential impacts may vary greatly across the ECAC region. However, disruption in one part of the network, or beyond, can extend across the network therefore it is essential that we consider this risk as a sector.

To prepare for the future impacts of climate change, both those considered in this paper and other impacts such as rising sea levels and more extreme temperatures, there are some key actions for the European aviation sector to take. Firstly, it is essential for states and aviation sector organisations to carry out climate change risk assessments so as to identify and understand the impacts that need to be addressed. Following this, appropriate adaptation responses can be identified and implemented, with individual organisations taking their own adaptation planning decisions based on their specific circumstances and business plans.

However, due to the interconnectedness of the European and global aviation systems, an integrated approach to building resilience is required. Therefore, in parallel, the European aviation sector as a whole should take a coordinated and collaborative approach to identify risks and minimise the impacts for all. Given the long-term investment horizons for aviation infrastructure, we need to start taking action now to ensure that our response is both timely and in proportion to the threat.

Conclusion

The objective of the EUROCONTROL 2021 Climate Risks for European Aviation study was to quantify future risks for the European aviation system, and sound an early-warning so that actions can be initiated in good time. The work has enhanced the understanding of how certain weather patterns impact operational performance of the network, providing a scientific basis for operational impacts already being experienced due to weather and those expected in the future.

The study has established that changes in frequency and intensity of storms will impact delays and flight efficiency. Although there will be regional differences, by 2050 when there is a delay due to a major storm it is expected to be greater than it is today. However, overall delays due to major storms and summer convection are expected to decrease. For en-route traffic, changes to high-altitude winds could impact flight times, fuel burn and CO2 emissions on routes between Europe and North America, north Europe and Asia and north Europe and the Canary Islands by 2050, with small reductions in flight times expected on most routes.

The quantitative analysis provided by the study provides vital information for the future operation of the European ATM network and concrete data on which to base short to mid-term decision-making so as to minimise the potential risks of climate change for both individual organisations and the network as a whole. Both individual aviation organisations and the European aviation sector as a whole should carry out climate change risk assessments and implement adaptation plans. However, to be as resilient as possible we should also take an integrated approach and coordinate adaptation action at sector-level. EUROCONTROL will continue to support European aviation in this collaborative effort.

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Climate-induced meandering jet stream and its influence on air distance

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Abstract

Climate change influences most parts of the society and therefore also different modes of transport, including aviation. Climate change has an impact on the intensity and frequency of significant weather phenomena, of which some have major implications for aviation safety and efficiency. These include e.g. jet stream wind conditions or thunderstorms, or strong convection. In this study, the change of the jet stream and respectively accompanying wind conditions as one of the most prioritized issue is discussed. Therefore, the described implications are investigated taking different jet stream scenarios into account regarding their impact on the anticipated change in air distance for a setting of North Atlantic flight missions. Initial results show, that especially during the winter period, meandering jet stream may have an effect on flight efficiency mainly due to its greater extension to higher latitudes.

Introduction

Globalization and interconnectedness are major driving forces of the modern world. Cosmopolitan awareness and international trade and action shaped economy, technology and development as well as cultural habits. World gets closer – not least of all the different possibilities of mobility. One crucial part of sophisticated mobility is aviation which acts as key factor in revolutionizing and expediting global trade, international business and individual travelling. Efficiency of aviation is not solely reliant on a co-ordinated and smooth dispatching of flights. For example, time-saving and economic air traffic service routes enhance air space capacity as well as air traffic flow and thus ATS performance in general.

With this in mind, a deep understanding of upper-tropospheric wind systems has a significant impact on the creation and adaptation in particular of long-haul routes as a part of the flight planning process. In this context, east-west orientated routes within the North Atlantic Track (NAT) system are adapted to the presence and characteristics of the subtropical and polar jet stream. Meanwhile the jet stream gained scientific and public prominence in combination with climate change and the occurrence of extreme weather events (Mann et al. 2017, Athanasiadis et al. 2010). Therefore, it seems essential for flight planning to consider the jet stream in the context of climate change.

The jet stream is a strong eastbound wind band in about 10 km altitude over mid latitudes with wind speeds up to 500 kilometers per hour. However, in the last years it could be observed that the behavior of the atmospheric jet stream has changed. Instead of fast and almost parallel wind patterns with reference to the equator, wind speeds decrease with the consequence, that the jet stream meanders over the northern hemisphere. Figure 1 illustrates a jet stream situation with strong zonal wind conditions on the left hand side and a situation with a meandering jet stream on the right hand side.

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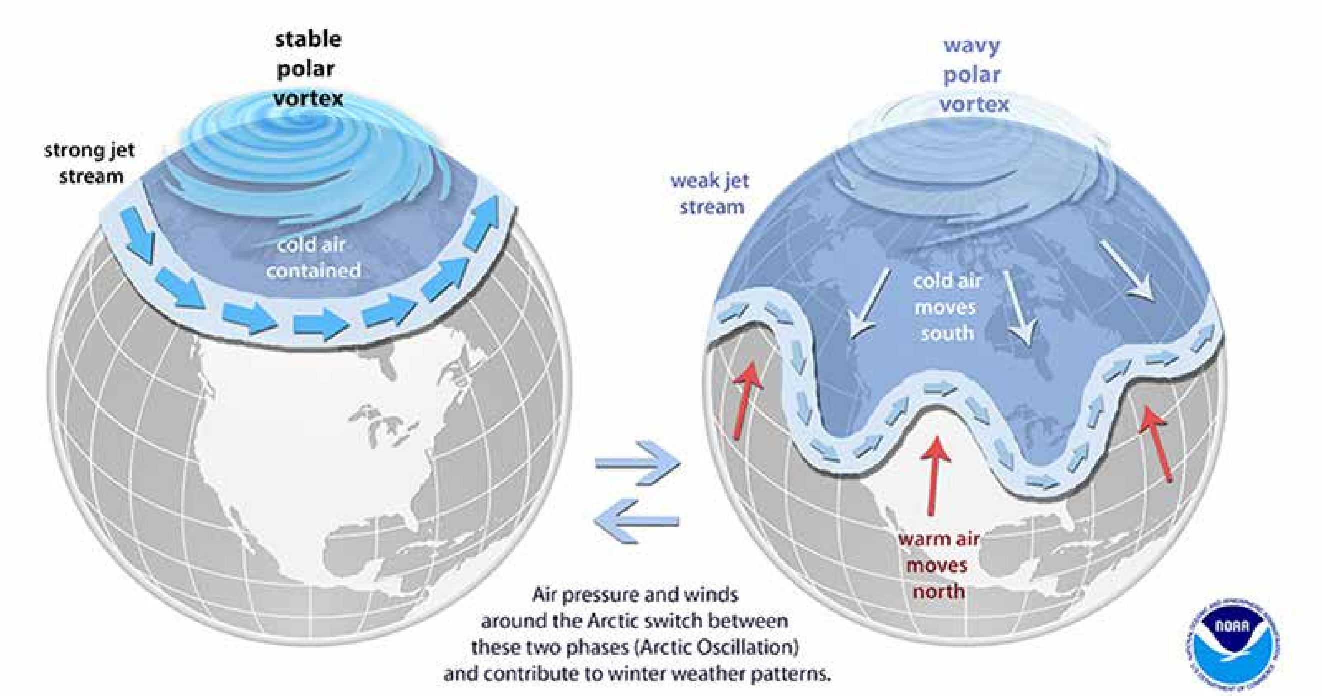


Figure 1: Jet Stream. Left: jet stream with strong zonal wind conditions. Right: Meandering jet stream with weaker wind conditions. Source: National Oceanic and Atmospheric Administration (NOAA).

Investigations show that the effects of climate change are causing these conditions, see e.g. AWI Scientific Report . The main forcing of the jet stream are temperature gradients between arctic and tropic latitudes. Due to increasing average temperatures at higher latitudes, temperature gradients decrease. Beside changing wind conditions, the meandering jet stream causes cold air breaks in winter and extreme long hot temperature periods during summer. Since wind effects are one of the major factors to be considered in flight planning, the shift of the jet stream regarding its direction and speed is of particularly high importance in aviation. Flights conducted in westbound direction, as for instance along the North Atlantic Track System (NATS) between Europe and North America, usually face headwind situations, which even increase the significance of wind on the resulting air distance. Considering the anticipated change of wind patterns regarding speed and structure, these changes are likely to have an impact on the effective range of aircraft, which will likely influence the fleet planning of airlines operating in the affected regions.

The impact of the climate effect on aviation occurs largely through changing climate and weather phenomena. Air temperature and density, for example, have an influence on the takeoff and climb performance of an aircraft, while thunderstorms and strong winds affect both the safety and efficiency of individual flight missions. The latter is especially considering flights within the jet stream, as flights are affected by correspondingly high headwind components. To minimize these effects along the trajectory, relatively high detour factors are accepted, which, however, lead to an increase of the flown distance. This results in the necessity of balancing the wind-induced air distance against the accepted detour factor, which in turn requires knowledge of the jet stream during flight planning. In this context, the effect of the climate-induced meandering jet stream on flight planning is largely unknown. This is the starting point of the present study to discuss in a first step the wind effect of the jet stream on the air distance and to derive starting points for further research.

The following chapter 1 discusses the jet stream and polar vortex and the observed changes due to climate. Chapter 2 provides a definition of the airborne distance metric used. Further, initial approaches of the changing jet stream on the air distance of individual flight missions are described. Chapter 3 contains the conclusions of the study and provides a recommend¬dation for further research approaches.

The jet-stream and polar vortex

The climate and weather patterns of the higher mid-latitudes are strongly influenced by the extratropical westerly winds. High seasonal temperature fluctuations and strong weather variability characterize the temperate climate zone of the northern hemisphere and also influence aviation (Kraus & Ebel 2003).

In the meteorological sense, the term jet stream refers to strong wind bands that have their highest wind speeds at the upper edge of the troposphere. These predominantly horizontal wind bands are highly variable in time and space, with wind speeds in some cases exceeding 130 m/s, and have a significant effect on the weather pattern of the lower troposphere due to their fluid dynamic properties (Bott 2016). As climate change progresses, the fluid dynamic properties of jet streams are expected to change as global warming progresses. This is expected to manifest itself primarily in the jet streams blowing more slowly, extending further north and south as meandering airflow, and the position of the jet main axes shifting more northward on a long-term average (Mann et al. 2017, McKnight & Hess 2009).

The WMO (World Meteorological Organization) defines an atmospheric jet stream as a narrow, meandering band of strong winds that occurs predominantly in the upper troposphere and lower stratosphere and can be described mathematically with the aid of fluid dynamics. In this way, a jet stream is characterized by a quasi-horizontal axis, the so-called jet axis, and high vertical and horizontal gradients of wind speed. For better classification, arbitrary velocity threshold of 30 m/s was introduced, which declares all high atmospheric winds greater than 30 m/s as a jet stream. As a three-dimensional flow structure, a jet stream often extends over several thousand kilometers in length, reaching vertical thicknesses of one to three kilometers and horizontal widths of less than a hundred kilometers.

The polar front jet stream of the northern hemisphere is subject to stronger spatiotemporal variations during the year than the subtropical jet stream. In this way, the polar front jet stream meanders between 35° and 75° northern latitude, with the jet axis in quasi-horizontal position at the 300 hPa level (tropopause). The highest wind speeds of the jet vary strongly between 40 m/s and 100 m/s, which is due to the high spatiotemporal variation of the polar front jet.

The hyperbaroclinicity of the polar front, which exists over the entire troposphere, is responsible for the driving mechanism of the polar front jet stream. According to the laws of thermal wind, zonal westerly winds can develop in this way already at ground level, which intensify massively with increasing altitude and reach their maximum at tropopause level. The high variability of the polar front jet stream in space and time can be explained by the so-called index cycle. This describes a constant interplay between the reduction and build-up of baroclinicity in the area of the polar front. Because the entire troposphere is in the baroclinic initial state, baroclinic waves can occur for a short time, which effectively degrade the baro-clinicity. Subsequently, it takes some time again for the polar front to return to a vertically powerful baroclinic state. In this way, the periodic emergence and decay of baroclinic waves or eddies also controls the formation and spatial extent of the polar front jet stream, which is why it is also called an eddy-driven jet (Bott 2016, Woollings et al. 2010).

Observed changes of the jet stream wind fields in the last years

Around the mid-latitudes of the northern hemisphere, low-pressure weather fronts, which bring cloudy, windy and potentially wet weather, generally move from west to east. These are carried along by the jet stream. The jet generally keeps a steady stream of weather systems moving across the Earth's surface. This means that any low-pressure system – or intervening high-pressure system that brings clear, still and sunny conditions – will generally only linger for a matter of days before being shunted on by the next system. However, sometimes weather systems can get stuck in place for an extended period of time. This is known as "blocking". This persistent weather can cause extreme conditions. Blocking is most common in spring, but is often most associated with dramatic heatwaves in summer and severe cold during winter. For example, blocking was a driver of the European summer heatwave of 2003, Siberia's heatwaves and wildfires in the summer of 2013, and Europe's extreme cold winter of 2009-10.

As blocking events can bring such extreme conditions, an important question is how their frequency and severity is being – and is likely to be – affected by a warming climate. Blocking has always presented a challenge for numerical weather and climate models, which tend to underestimate both the occurrence and persistence of events. Additionally, blocking is a sporadic weather pattern and, hence, highly variable from year to year, even from decade to decade. This means that blocking events will naturally vary a lot from one year, or decade, to another, so that a clear view on any long-term trend is muddied by short-term fluctuations (Woollings et al. 2018). Hanna et al. state, that the increase in blocking could have "been triggered by low-level regional warming promoted by surface feedbacks" such as increased snowmelt and ice melt on Greenland, and Arctic regional sea ice losses or changes in the jet stream, but this is currently unknown.

Woolings et al. (2018) show climate projections for northern-hemisphere blocking in winter and summer, according to three different methods of characterizing blocking events between 1961-1990 and 2061-2090, under the very high emissions RCP8.5 scenario. For summer, the results suggest that blocking will shift pole wards, reducing the number of events in the mid-latitudes, but increasing them in high latitudes. This is reflected by Masato et al. (2013) too.

One point that has received less attention is the size of blocking events. Nabizadeh et al. (2019) suggest that the spatial extent of blocks is likely to increase with climate change. Using two climate models and the RCP8.5 scenario, the research project that the area of blocking events could increase by up to 17% and 7% in the northern hemisphere summer and winter, respectively (by 2076-2100, compared to 1981-2005). For the southern hemisphere, projections indicate a decline in block area in summer (up to 2%) and an increase in winter (up to 8%). For example, over the North Atlantic region in summers, the jet stream becomes wider and shifts to the north, leading to an increase in the size of the Euro Atlantic blocking events. Over the North Pacific region in winters, the jet stream becomes wider and faster and shifts to the north, all together leading to larger blocking events over the western Pacific Ocean and eastern North America.

Selected weather situations for impact study

To show the impacts of different states of the jet stream we present the north hemispherical situation on two days in 2018 as identified by Renk (2020). As input data the ERA-Interim (Berrisford et al. 2011) data set is used. ERA-Interim is a global atmospheric reanalysis that is available from January 1979 to August 2019.

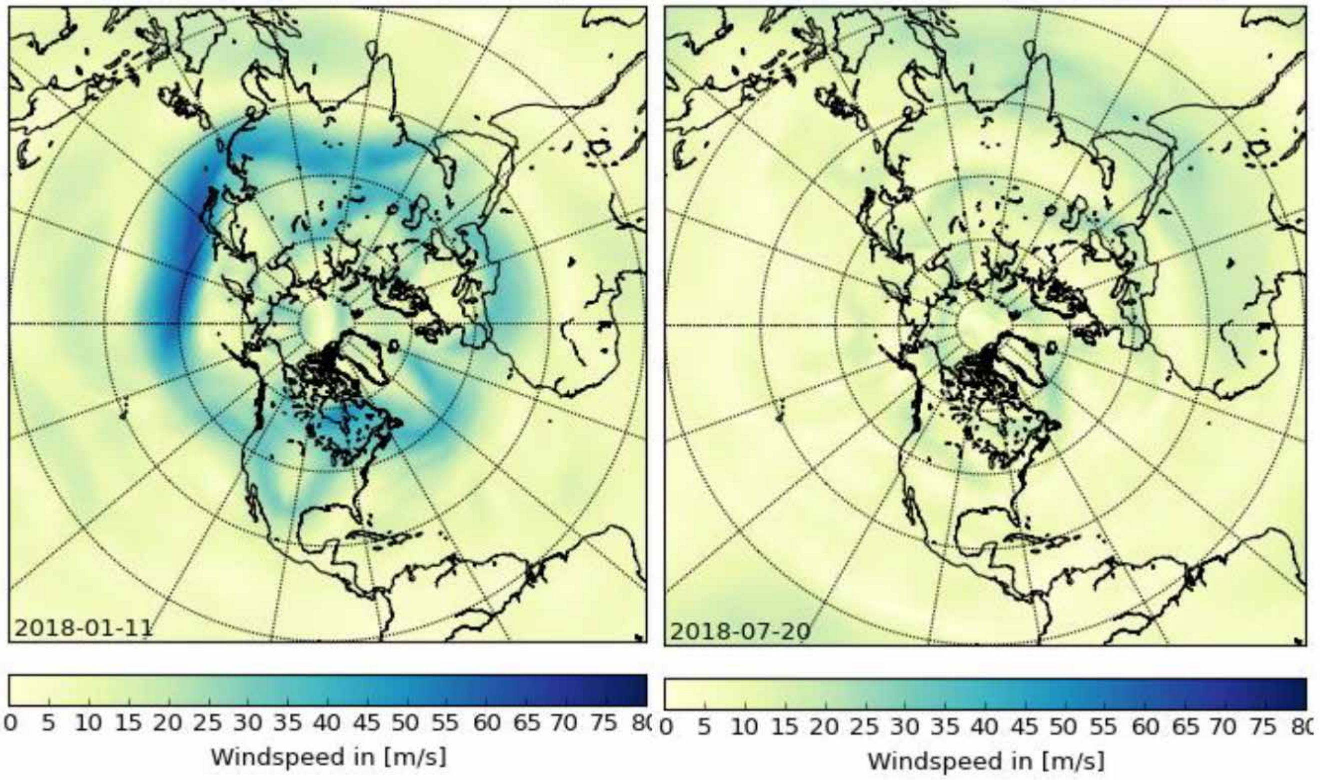


Figure 2: Mean Windspeed between 400 and 100 hPa for two selected days according to Renk (2020).

An observation of the mean horizontal wind field between pressure levels 400 and 100 hPa shows a clearly identifiable spiral jet stream structure in the northern hemisphere as an annual average. It is noticeable that the monthly mean jet, which appears to be spiral, is more of a jet stream of at least two, often three substructures. The spiral shape is still recognizable, but the jet is no longer a single structure. Rather, it consists of at least two wind bands, which, sometimes intertwined and sometimes disconnected from each other, build up a common spiral shape. Another striking feature is the meandering of the jet stream, whose wave number ranges from five to six. The pronounced meandering of the jet stream manifests itself in distinct trough and ridge structures, which in the winter of the northern hemisphere cause a reduction of the energy gradient between the equator and the pole. In this process, the polar cold air reaches far south and the tropical warm air far north, forming the polar front. In the present study, we chose the dates 2018-01-11 and 2018-07-20 to evaluate air distances of a clearly meandering jet stream.

Impact of a meandering jet stream on air distance

In a tailwind case as well as due to lower air density at average cruising altitudes, engine thrust is reduced. Tailwinds add to the aircraft speed and thus increase the ground speed, which consequently shortens the flight time (Coffel & Horton 2015). A headwind, on the other hand, reduces the relative airspeed over ground, thus increasing flight duration. Thus, for the design of flight routes, it is essential to know the atmospheric flow conditions of the upper troposphere. In this way, not only the high weather variability of the mid-latitudes, but also the flight paths used in this climate zone depend on the large-scale wave structures of the polar front jet stream. The westerly wind drift of the troposphere is linked to the flow dynamic behavior of the jet stream, which is why this atmospheric air flow directly influences aviation in addition to weather patterns (Weischet & Endlicher 2013, Kraus & Ebel 2003).

The North Atlantic jet stream plays an important role for the meteorological flight planning in the North Atlantic track system (NATS) as they have a significant influence on fuel planning based on the distance over ground as well as the air distance. As strong wind bands with eastbound flow, they can be used as systems of natural acceleration, which allows for economic eastbound operations even away from orthodromes by using the area of maximum tail wind. In the westbound direction, the jet stream is avoided as much as possible, which, depending on the respective wind field structure, may lead to both, high extensions of the actual flight trajectory or a potential reduction of the ground distance compared to NATS-based initial planning. The objective of economic flight planning is to minimize the resulting air distance in both directions. To do so, the knowledge of average wind speeds at cruise flight level as well as past flight times and a reliable jet stream forecast is crucial at this point.

Air distance definition and properties

The subject of investigation throughout this study is an atmospheric phenomenon, the jet stream in the North Atlantic region, and its impact on the effective distance of an aircraft to cover between two points in atmosphere. In order to obtain results, that are mostly independent from aircraft specific factors, the investigated parameter is the air distance, which is derived according to the model presented in Swaid et al. (2016). Using this kinematic approach, the aircraft is considered as a massless point that moves along a predefined, three-dimensional point profile derived from real trajectory data with a constant Mach number Ma = 0.84. Assuming the air to be an ideal gas and applying the simplification of a constant Mach number throughout the complete mission, the true air speed (TAS) of the aircraft can be derived according to

$$v_{TAS} = Ma \cdot \sqrt{\varkappa \cdot R \cdot T}, \qquad (1)$$

in which the adiabatic index is set to $\varkappa = 1.4$ and the gas constant is assumed to be R = 287.05 J/kgK. The temperature T, as well as the wind data, are obtained from real atmosphere data based on ECMWF ERA-interim, applying a bi-linear interpolation routine, which vertically follows the specific pressure level of a corresponding Flight Level under standard atmospheric conditions. Horizontally, the routine interpolates between the four sampling points with the closest position regarding their latitude and longitude.

The two components v_(W,North) and v_(W,East) represent the wind speeds in Northern and Eastern direction, respectively, and are subsequently composed to a wind vector with total value

$$|v_W| = \sqrt{v_{W,North}^2 + v_{W,East}^2} \tag{2}$$

and wind direction

$$\chi\mathrm{W} = sin^{-1}\left(\frac{v_{W,East}}{v_{W,North}}\right). \tag{3}$$

With χ_C, which denotes the course over ground, the resulting ground speed (GS) is finally determined by superimposing the local wind vector with TAS according to

$$v_{GS} = v_W \cdot \cos(\chi_C - \chi_W) + \sqrt{v_W^2 \cdot \cos^2(\chi_C - \chi_W) + v_{TAS}^2 - v_W^2}. \tag{4}$$

The evaluation of atmospheric influences is repeatedly conducted according to these steps along the track, which is divided by its ground distance into discrete intervals of $\Delta_{\mathrm{SGround,Inc.}}$=1000 m. Finally, the aircraft transition time is calculated for each interval i according to

$$\Delta t_i = \frac{\Delta_{S_{Ground,Inc.}}}{v_{GS,i}} \tag{5}$$

and numerically integrated along all trajectory points, yielding the wind corrected air distance

$$s_{Air} = \sum_{1}^{n} v_{TAS,i} \cdot \Delta t_i. \tag{6}$$

Jet stream implications on air distances

In this chapter, the impact of the jet stream on the air distance is quantified for a set of origin destination (OD) pairs. The depicted OD pairs in Figure 3 (a) and (b) are bi-directionally set between EGLL (London) and KORD (Chicago), while the trajectories in Figure 3 (c) and (d) are set between LFPG (Paris) and KFJK (New York). Each OD combination is depicted for a normal North Atlantic jet stream situation in cases (a) and (c), as well as for a meandering jet situation in cases (b) and (d).

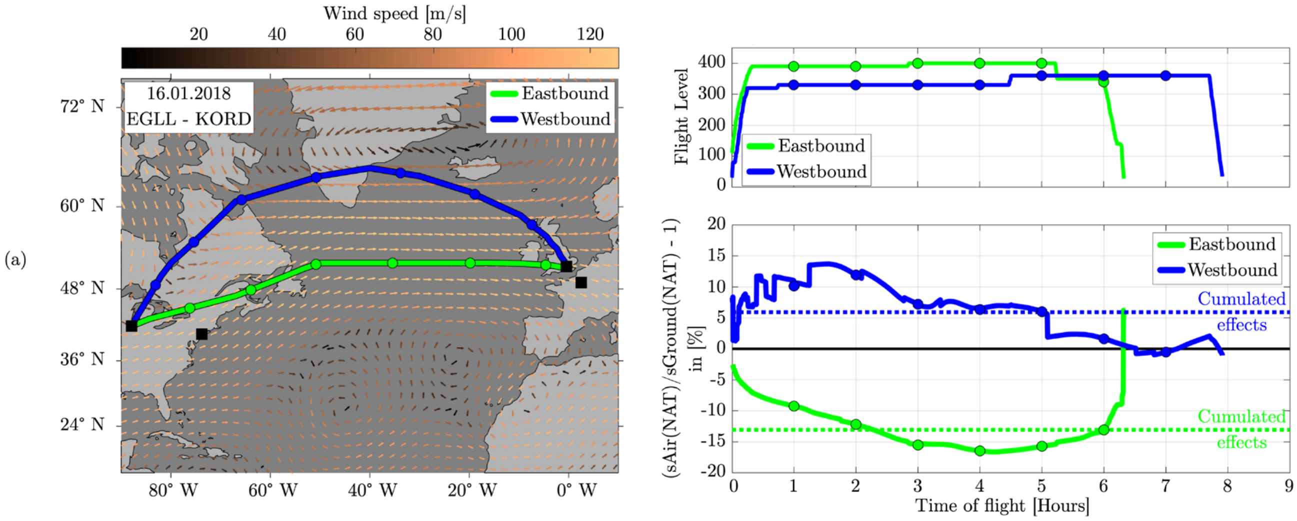
For each group (a-d), a detailed overview of the wind situation on FL390 is depicted on the left-hand side, where each vector marks the local wind direction and has a color code, that assigns respective wind speeds, ranging from 0 to 120 m/s. Two tracks are in each graph, that were derived from post-operational flight plan trajectories of the EUROCONTROL DDR2 repository. These tracks are matching with the depicted atmosphere data regarding their date. While green tracks mark eastbound flight directions, tracks depicted in blue mark the westbound counterpart.

At the top right of each group, the profile of the Flight Level (FL) evolution is depicted over the flight time for both flight directions. Due to the constraints of the available atmosphere data for this study, the calculation of wind effects is limited to altitudes above 2500 feet (FL25).

Finally, at the bottom right of each group, percentage increase of air distance compared to the ground distance is plotted according to

$$\Delta Dist_{NAT,NAT} = \left(\frac{s_{Air,NAT}}{s_{Ground,NAT}} - 1\right) \cdot 100\% \,. \tag{7}$$

The air distance and ground distance for this metric respectively, can either refer to the track inside the Air Traffic Services (ATS) and North Atlantic Track System (NAT) and are therefore marked NAT, or they can refer to the track along the orthodrome and are marked Ortho.



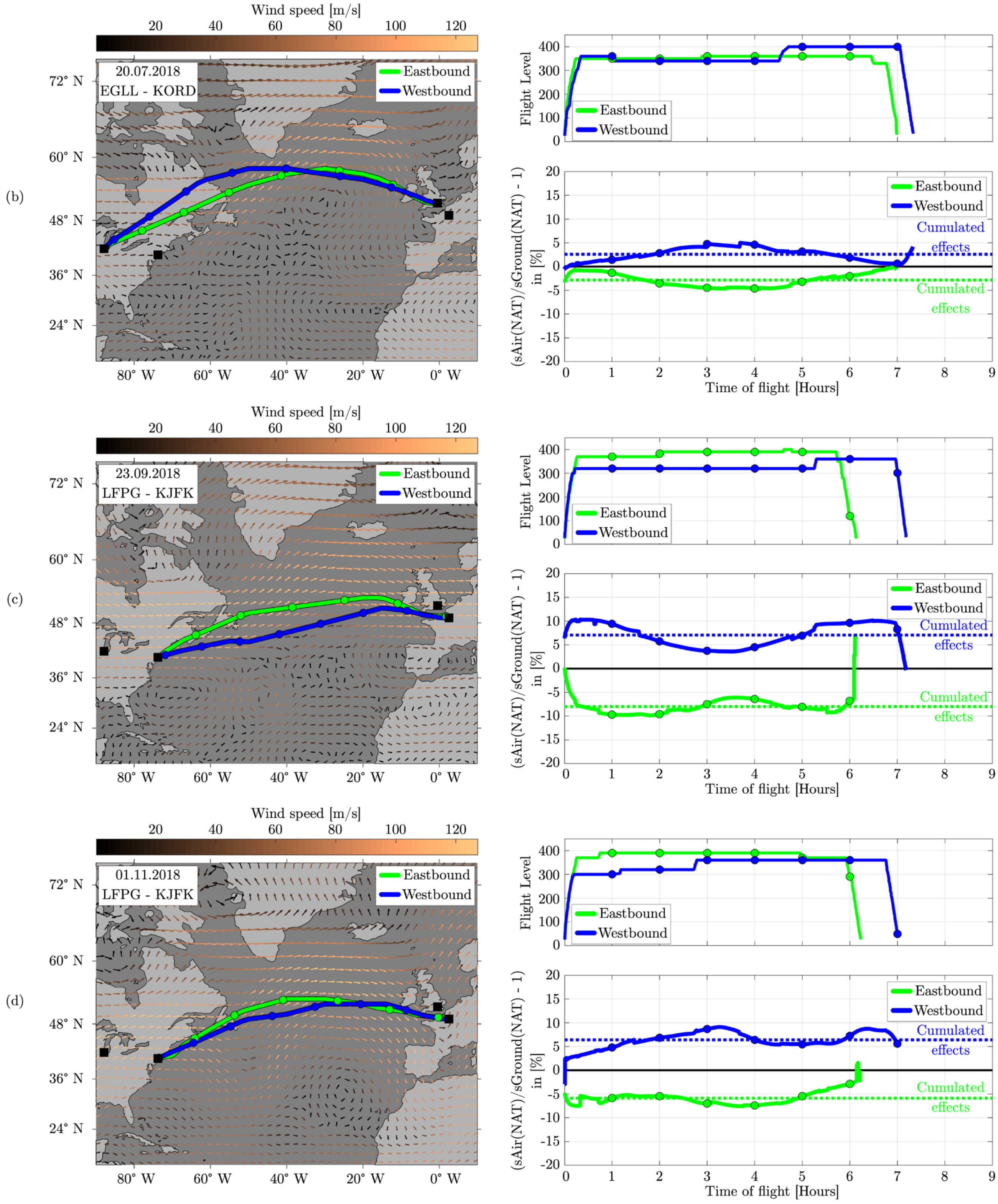


Figure 3: Impact of the jet stream on the air distance of a set origin destination (OD) pairs on selected days: a) EGLL-KORD 16/01/2018 (conventional wind conditions), b) EGLL-KORD 20/07/2018 (meandering wind conditions), c) LFPG-KJFK 23.09.2018 (conventional wind conditions), d) LFPG-KJFK 01.11.2018 (meandering wind conditions). The right side shows flight times as well as the wind effect based on the percentage increase of air distance compared to the ground distance for bi-directional tracks

The circular markers along the tracks indicate flight time in hourly segments. These markers particularly allow to draw causal connections between the wind field depicted on the left-hand side and its corresponding impact on each segment of the track, depicted on the right-hand side. While the bold lines indicate the local impact of atmospheric effects on the distance increase, the dashed lines show the cumulated effects over the full trajectory.

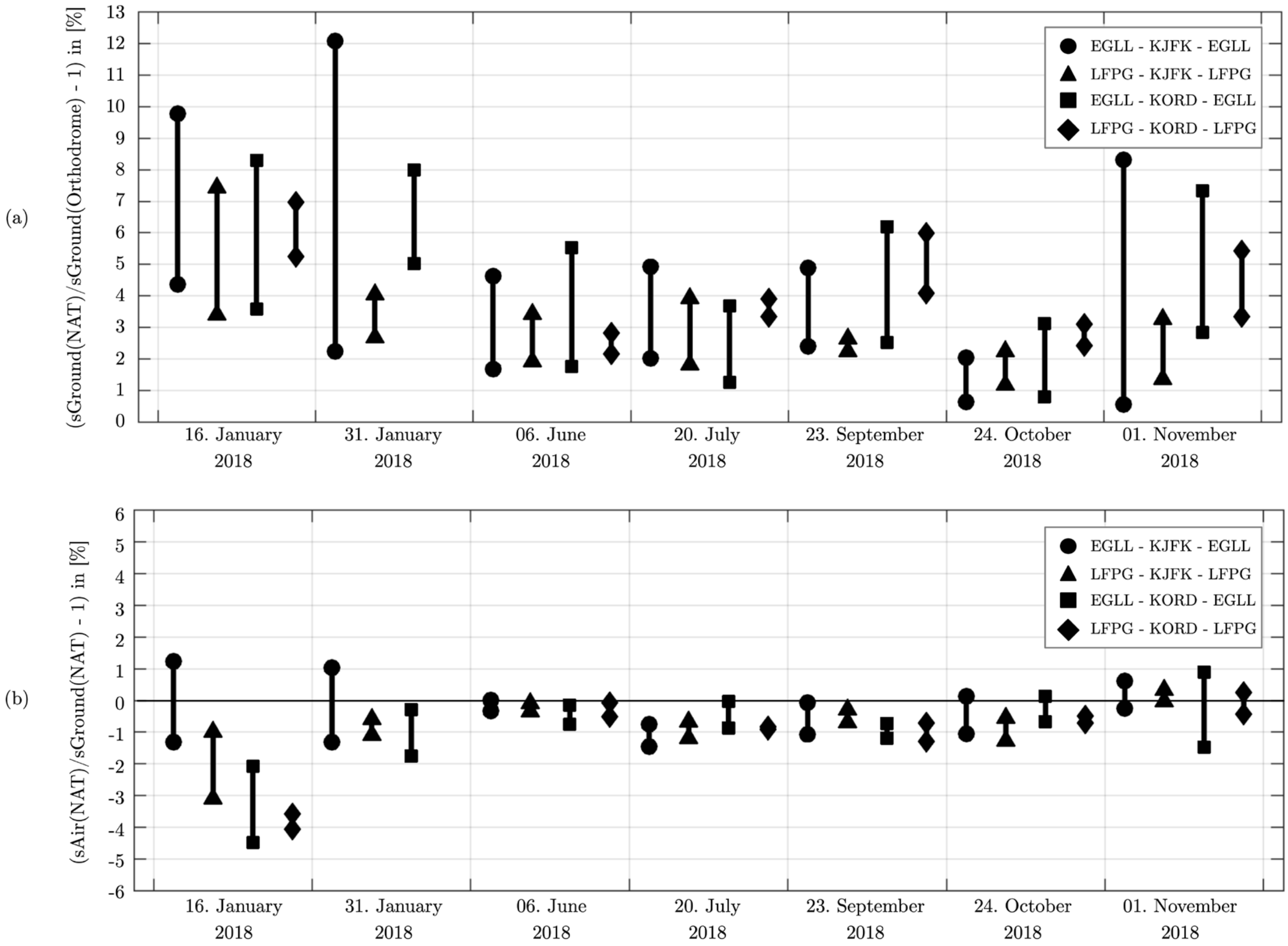
Figure 3 (a) shows the east- and westbound trajectory between airports EGLL and KORD on a day with conventional jet stream conditions in the North Atlantic region, showing high wind speeds and a lightly curved shape of the jet stream. The wind field is particularly characterized by a relatively large extension of high wind speeds across the latitude on the shown FL390. In the course of the first two flight hours, the westbound track deviates into northern regions towards Iceland in order to evade the strong winds and to minimize the headwind component along the track. After 1.5 hours flight time, the wind effects along the track reach their maximum value, increasing the air distance for each covered mile of ground distance by a factor of almost 14%. Along the next segment, the aircraft reaches regions with lower wind speeds in the area of Greenland, causing a local distance increase of approximately +6%. On arrival at Hudson Bay at a flight time of 5 hours, the headwind component and therefore also the local wind induced increase of distance is significantly reduced to values below +2.5%, mainly due to a change of aircraft course. Along a small segment shortly before the 7 hours mark, the wind impact takes values with a slightly negative margin due to a tailwind component. The overall impact of atmosphere effects for this trajectory cumulates to +6%.

In eastbound flight direction, the trajectory is mostly located in the center of the wind field in order to maximize the share of tailwind segments, utilizing wind effects that are in favor of minimizing the air distance. The wind strength increases steadily over the flight time up to the 4-hour mark, such that the beneficial wind reaches its maximum effect with a distance factor per mile of about 17%. Reaching the British coastline at the end of the sixth flight hour, this effect significantly weakens during the approach phase, as the aircraft descends to lower Flight Levels, leaving the altitude levels of the strong geostrophic winds. Shortly before landing, the wind effect reverses, imposing a headwind component on the aircraft due to local wind conditions. After just over 6 hours, the mission is completed about 1.7 hours earlier than the equivalent westbound flight with a cumulated wind effect of -13%, reducing the air distance significantly in comparison to the covered ground distance. Furthermore, it should be added, that the wind effect profile does not reflect clear responses to conducted step climbs during the cruise phase, which is most likely connected to the limited availability throughout this study of merely two atmospheric data layers along the altitude range from 30,000 to 53,000 feet.

The same OD pair is depicted in Figure 3 (b), yet here we observe a meandering wind pattern with significantly lower speeds and a winding stream, that reaches far into the northern regions around Iceland, from where it swings south to the coast of Africa and Southern Europe. In order to efficiently cope with this weather situation, the trajectories along both flight directions show similar tracks and are spatially located between the two reference cases, that were discussed beforehand. As expected, due to the generally lower wind speeds and frequently occurring crosswind situations along the track, there are hardly any route segments observable, that provide wind situations with impact values exceeding a total value of ±5%. In terms of the evolution of wind effects along the route, both tracks seem to be symmetric with regard to the 0% line and either track cumulates to an overall effect of approximately ±2.5% with a deviation regarding their flight times by less than 0.5 hours.

In Figures 3 (c) and (d), trajectories between the airports LFPG and KFJK are analyzed for two exemplary atmosphere days, one of them selected to be conventional, but with weak wind conditions in October 2018, and another weather situation with meandering patterns in November 2018. Based on these further examples, the impact of wind effects can be confirmed to decrease for meandering weather patterns in comparison to conventional jet stream situations. However, these examples show considerably smaller discrepancies between the conventional and the meandering wind situation, underlining the necessity for further analysis of more data samples.

Figure 4: Distance variations for all terminated flights on considered bi-directional tracks based on a) percentage offset between great circle and NATS track as an implicit measure of wind impact, and b) percentage difference between air- and ground distance along the NATS tracks (the higher, the greater the air distance)



Considering the observed varying effects of atmospheric influences on the air distance discussed before, the overall impact of the jet stream needs to be quantified for the full range of investigated samples. This analysis is carried out bi-directionally, weighing up the predominantly favorable wind conditions for eastbound flights and the mostly adverse wind situations when operating westbound, summarizing the impact on an aircraft that operates an outgoing and a return flight under the effect of that wind field. Since headwinds have a slightly higher impact on the air distance (Swaid 2013), these wind effects in general do not fully compensate each other when operating bi-directionally along a single track. In our analysis however, two different tracks are investigated in westbound and eastbound direction, each of them individually wind optimized. Therefore, these tracks are not only charged with different levels of wind impact, but also with different levels of ground distance, slightly compromising the comparability of the wind impact percentage according to Equation (7) due to the deviation between the base values. In Figure 4 (a) therefore, the bi-directional ground distances of each analyzed OD-pair are summed up and compared to the respective ground distance of the orthodrome to create a common, comparative value. Since there have been multiple, post operational trajectories analyzed for each combination of OD-pair and atmosphere day, the span between minimum and maximum value is depicted, respectively. It can be observed that the tracks show detour factors between 0 and 12.2% regarding their ground distance. Both days in January and 1st November show greater variances for EGLL–KJFK–EGLL as well as EGLL–KORD–EGLL, which implicitly indicate stronger winds on these days. Of these three days during the winter period, the 1st November with meandering jet stream shows the lowest values available, indicating least wind impact during winter in both flight directions. Due to the potentially lowest tail wind effect, this does not mean that the greatest flight efficiencies can be achieved on this day in bi-directional routes, which is indicated by Figure 4 (b). This Figure provides the relation between air and ground distance on the NATS tracks. Most of the values vary between -2% and 0% resulting in slight air distance savings compared to ground distance. Comparing the winter days with each other, the highest values on 1st November mostly exceed those of the other winter days, which indicates greater inefficiencies in case of meandering jet stream.

The results for the four days in June, July, September and October, representing the summer season, are less clear with regard to the meandering wind effect on 20th July compared to the one of the other days. In particular, the day in October, which was not identified as a day with meandering jet stream shows a smaller offset between great circle and NATS tracks as can be observed in Figure 4 (a). Related to the air distances on the NATS tracks shown in Figure 4 (b), no significant effect on flight efficiency can be identified for 20th July (meandering jet stream) as a result of changing air distances.

Conclusion

Meandering jet stream situations have been investigated based on a limited set of flight missions. Characteristics of a meandering jet stream can be recognized through the evaluation of the wind field in its less continuous flow pattern with its stronger curvature towards greater geographical latitudes. With respect to air distance, it is obvious, that clear effects of meandering jet stream are likely to occur during the winter season. Despite the generally lower wind speeds of meandering jet stream, these wind situations provide potential in order to utilize tailwind effects in eastbound operated flights. On the other hand, due to the large extension of the meandering wind field, it is likely, that westbound operated flights, which intend to avoid these wind fields, are only to be realized with greater inefficiencies. To make effects of meandering jet stream more visible, the authors recommend to initially analyze a greater set of bi-directional as well as one-directional NATS routes of the winter period. Moreover, a parametric differentiation and a distinction of days with meandering jet stream to those of conventional jet stream is needed. The present study provides initial indications for further investigations in this regard.

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Session 2

Options for reducing CO_2 emissions

Real-time thunderstorm information enables fuel savings for long-haul flights

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Introduction

Thunderstorms (Cb – Cumulonimbus) and their accompanying features like severe turbulence, lightning, icing, hail and heavy precipitation endanger air traffic and are avoided by aircraft whenever possible. They are thus a major reason for detours, holding patterns, and landings at alternates all resulting in additional fuel burn, delays and costs [Eurocontrol, 2018a and 2018b]. In this study, we show that real-time Cb detections and forecasts up to one hour (=nowcast) based on geostationary satellite data are very well suited to find optimal routes around the Cbs with the least possible additional fuel burn. We focus on long-haul flights crossing the inter-tropical convergence zone (ITCZ) for two reasons. Firstly, in the tropics Cbs are active daily throughout the year, i.e. avoidance manoeuvers are likely every day. And secondly, many routes of long-haul flights within or crossing the ITCZ lead over oceanic areas where flight routing is less restricted than e.g. in the European airspace, i.e. pilots are relatively free in choosing an individual avoidance route. Two independent approaches are presented to estimate the en-route fuel saving potential for long-haul flights crossing the ITCZ. In the first approach, a mean value of potential fuel savings is estimated based on a Cb statistics over the tropical Atlantic in combination with the number of flights through this region performing detours around Cbs. In the second approach, the fuel burn of selected real flown flight routes from IAGOS [In-Service Aircraft for a Global Observing System; https://www.iagos.org; Petzold et al., 2015] showing tactical manoeuvers around Cb cells is compared to the fuel burn, if these flights are laterally optimized with a Trajectory Optimization Module on the basis of the Cb nowcasts.

Models and data

Cb-global

Cb-global is a technology to detect, track, and nowcast Cbs based on geostationary meteorological satellite data [Zinner et al., 2008 and 2013]. Since Cb-global is able to process data from the METEOSAT, Himawari, and GOES satellites, Cb detection and nowcasting can be provided all over the globe with a spatial resolution of up to 500m and 5, 10 or 15 minutes update rate depending on the satellite instrument. One high resolution visual, two infra-red, and one water vapour channel are combined in order to identify four different development stages of Cbs: cells that can potentially develop to a Cb, rapidly vertical growing cells, mature thunder cells, and convectively induced turbulence. An example with

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rapidly vertical growing cells (orange) and mature Cbs (red) is illustrated in Figure 1. The tracking and nowcasting of the thunder cells are based on a pyramidal image matching technique taking into account cloud developments like growth and decay [Zinner et al., 2008]. The nowcasts are available up to one hour in five minutes steps.

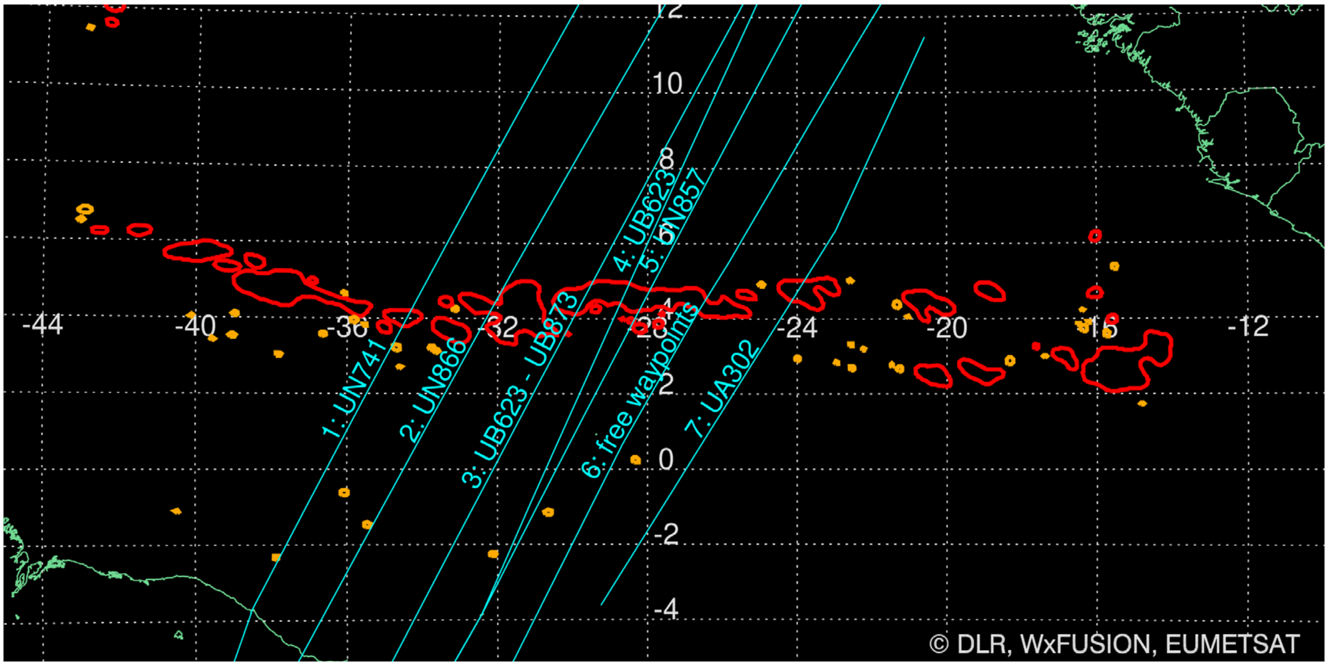

Figure 1: Cb-global detections over the tropical Atlantic, example from 13 December 2012 at 6:16 UTC. The seven typical flight routes between Europe and South America are indicated as cyan lines.

The accuracy of Cb-global has been proven by a comparison with lightning observations [Zinner et al., 2013], and its qualification as a flight planning tool has been validated based on historical data [Tafferner et al., 2010] as well as in real time data link tests with research and commercial aircraft [Forster et al., 2017].

Trajectory Optimization Tool (TOM)

In the course of this study, the Trajectory Optimization Module (TOM) [Lührs et al., 2016] is applied in order to determine continuously optimized trajectories which lead to minimum fuel consumption while avoiding Cb regions based on Cb-global data. Since TOM is based on an optimal control approach, aircraft's motion is described as temporal evolution of state variables x(t) characterizing the aircraft's state (e. g. position, time, speed) and control variables u(t) which affect the motion of the aircraft (e. g. heading, thrust, acceleration). Consequently, optimized trajectories are obtained by identifying a control input u(t) which minimizes the cost functional J defined as the sum of the fuel consumption (m0-mf) and the temporal integral over a penalty function Ψ according to equation 1. Here, Ψ is chosen as a binary penalty function which is set to 1 in Cb regions and to 0 if no Cb occurs. The weighting factor cΨ is selected sufficiently large in order to totally avoid Cb regions by optimized trajectories.

$$J(x(t), u(t), t) = (m_0 - m_f) + c_\Psi \cdot \int_{t_0}^{t_f} \Psi(x(t), u(t), t)\, dt \qquad (1)$$

Additionally, dynamic constraints (e.g. equations of motion) as well as control (e.g. thrust limitations), state (e.g. speed) and path limitations (e.g. pressure altitude) have to be fulfilled. These boundary conditions are essentially defined by Eurocontrol's base of aircraft data (BADA) 4.0 performance models [Nuic and Mouillet, 2012] and complemented with additional assumptions according to the problem at hand (e.g. constant altitude). The resulting continuous optimal control problem is transformed into a discrete non-linear programming problem (NLP) using the MATLAB toolbox GPOPS-II [Patterson and Rao, 2014]. Finally, the NLP is solved with the NLP-solver IPOPT [Wächter and Biegler, 2006].

IAGOS

For approach 2, it is essential to have access to accurate flight paths including the avoidance manoeuvers around Cbs in the ITCZ. The fuel consumption of the routes with avoidance manoeuvers can then be compared to the fuel consumption of routes optimized by using Cb nowcasting information. Especially over the oceans exact aircraft routes are not available from databases like FlightAware or FlightRadar24, because they provide only radar data from Automatic Dependent Surveillance - Broadcast (ADS-B) receivers which are not available over the oceans. Global Position System (GPS) data of aircraft are transmitted via satellite communication from the aircraft to the ground, but these data are generally only sent to the airline headquarters. The IAGOS (https://www.iagos.org/) data base, however, offers the unique advantage that for all included flights the actual aircraft positions are recorded all along the flight.

Based on visual inspection of flight tracks in the IAGOS data base (https://doi.org/10.25326/06) of the years 2011 – 2014 we identified about 600 flights showing Cb avoidance manoeuvers and randomly inspected more closely 75 of these flights, all crossing the ITCZ over the tropical Atlantic. Major detours of more than 30 minutes were flown by 20% of the selected 75 flights, and 13 flights out of the 75 flights show two or more detours around Cb cells on their way. From all these flights we intend to estimate a range of the fuel saving potential, if Cb nowcasting data are used for the route planning. Since trajectory optimization is computationally expensive, we performed the trajectory optimization with TOM for three of the selected flights, two of them showing the most extreme avoidance manoeuvers (detour > 60 minutes) of the inspected 75 flights and one of them showing a detour of about 20 minutes for which the TOM optimization reveals that the avoidance was not necessary at all

Approach 1: Fuel saving potential based on a Cb statistics

The ITCZ is a region that encircles the earth near the equator in a narrow belt where the trade winds of the Northern and Southern Hemisphere converge and favour the development of vigorous Cbs daily throughout the year. Flights between the Northern and Southern Hemispheres have to cross this region, and their typical routes are almost perpendicular to the Cbs lined up along the ITCZ as illustrated in Figure 1 for the flight corridors over the tropical Atlantic. The Cb activity in the ITCZ increases to its daily maximum in the early morning hours, because the atmosphere is cooled by radiation, and the warm water acts as a heating surface favouring the development of Cbs [Hendon and Woodberry, 1993]. Note that this is also the time when most of the flights from South America to Europe take place due to local time difference between Europe and South America.

A Cb statistics has been established for the seven flight routes from Figure 1 on the basis of Cb-global mature Cb detections every 15 minutes for the months June, July, and August (JJA) 2015, i.e. 92 days in total. In a latitude band between 0°N and 14°N, where the ITCZ is typically located during this season, it was checked whether mature Cbs are located somewhere on the typical flight routes between Europe and South America. It turned out that on 73 days in JJA 2015, i.e. in 79% of the considered days one or more flight routes were simultaneously blocked by Cbs. Three or more flight routes were simultaneously blocked on 27 days, i.e. major avoidance manoeuvers can be expected in these cases.

In a previous study [Forster et al., 2017], we learned from a single flight with an A340-600 between Rio de Janeiro and Frankfurt that the fuel saving potential was about two tonnes [t], if the Cb-global information was used to adjust the flight route to the current Cb situation. The Cb activity in this case was considerable and can be compared to the situation as illustrated in Figure 1 where six to seven flight routes were simultaneously blocked by Cbs in a latitude belt from 2°N to 4°N. Based on this experience, we define category 1 corresponding to 6-7 blocked routes and 2 t of fuel saving potential or about one hour of flight time saving, respectively [Table 1]. Category 1 blocking situations occurred on 7 days in JJA 2015. Accordingly, we define category 2 and category 3 of fuel saving potential, if three to five flight routes are simultaneously blocked by Cbs, and if only one or two routes are blocked at the same time, respectively [Table 1]. It is anticipated that the detours around the Cb cells are smaller the less flight routes are simultaneously blocked, i.e. also the potential fuel savings are smaller the less flight routes are simultaneously blocked. The potential fuel savings of categories 2 and 3 are based on estimates and computations of two test pilots and two pilots from a commercial airline.

In ICAO [2016] it is documented that 5316 flights took place in the South Atlantic region in June 2014, i.e. about 177 flights daily. Assuming that this number is still representative for JJA 2015, one can calculate total fuel savings for this period for each of the three categories. The numbers for the three categories are summarized in Table 1. From Table 1, we can estimate an average fuel saving potential of about 2902 t per month. This corresponds to an average fuel saving potential of 97 t per day and 0.548 t per flight.

Based on flight plans, it can be estimated that a major airline generally performs about 60 flights per week crossing the ITCZ somewhere on the typical flight routes between Europe and South America as indicated in Figure 1. With an average fuel saving potential on these routes of 0.548 t per flight and a fuel price of 66 Cent per kg (fuel price on 2 November 2021), this would sum up to 1.12 million Euro fuel savings per year for this airline just on the routes crossing the tropical Atlantic. Worldwide a major airline generally performs about 460 flights per week crossing the ITCZ. Assuming that the fuel saving potential per flight is similar also on other worldwide routes through the ITCZ, this would sum up in 8.6 million Euro total savings per year per airline. This is comparable to other already implemented fuel saving projects which can e.g. in total result in a positive financial effect of 7.7 million Euro for one airline per year [DLH, 2018]. Hence, in view of the currently rising fuel prices (today the price is twice as high as in September 2020) the use of real time Cb information for the flight planning has a major potential regarding cost savings.

Table 1: Three categories of fuel saving potential and their occurrence in JJA 2015.

Category	1	2	3
Number of blocked routes	6-7	3-5	1-2
Fuel saving per flight [t]	2.0	1.0	0.33
Flight time saving [min]	60	30	10
Occurrence in JJA 2015 [days]	7	20	46
Fuel saving in JJA 2015 [t]	2478	3540	2687

Approach 2: Fuel saving potential based on flight route optimization

Optimization of IAGOS flight routes with TOM

For approach 2, we run Cb-global for tiles around the areas of interest where avoidance manoeuvers due to Cbs are observed in the IAGOS data. These tiles have a size of about 2000 km x 2000 km, i.e. at the entry point into a Cb-global tile an IAGOS flight is about 1000km away from the Cbs to be avoided which corresponds to approximately one flight hour, i.e. the maximum nowcasting horizon of Cb-global.

Cb-global data is available as an object based output, i.e. thunder cell detections and nowcasts are stored as geo-referenced polygons encompassing the hazardous area for air traffic. For the integration of Cb data into TOM, Cb-global polygons are preprocessed and mapped onto a binary lateral grid: values of 1 indicate Cb areas, values of 0 indicate unaffected areas. A grid resolution of 0.1 degrees has been selected providing both, a sufficient accuracy and adequate gradients (when interpolating between Cb and no Cb areas) which are required for the optimization.

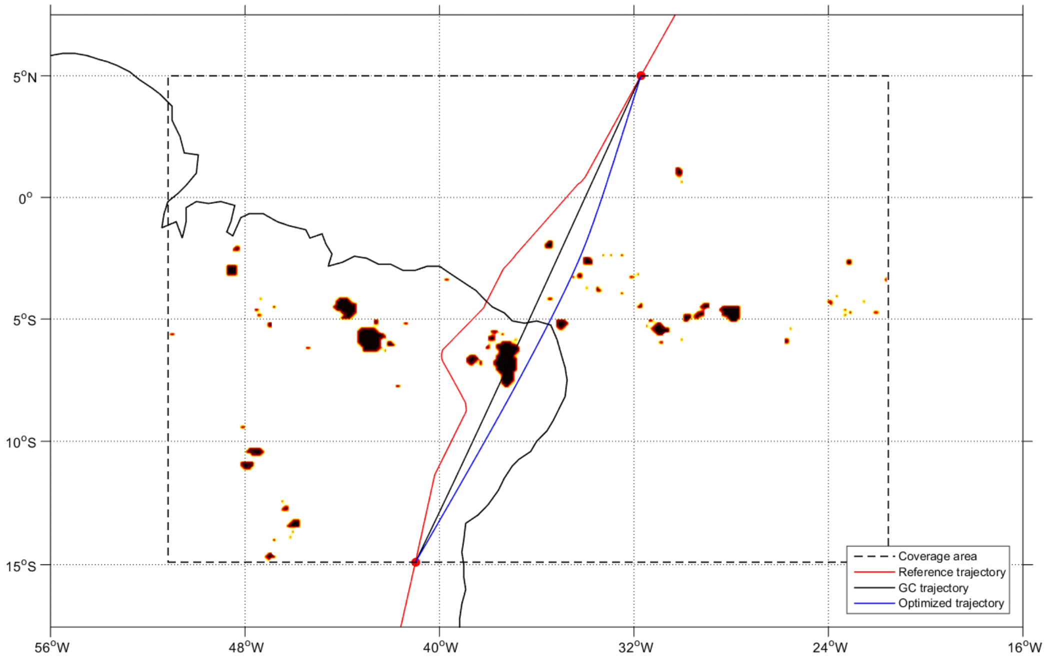

Figure 2: Trajectory optimization

For the definition of the optimization problem, in a first step, the intersection points of the reference trajectory (based on IAGOS-data) with the Cb-global tile are calculated (see Figure 2, red points). These points serve as initial and final point of the trajectory optimization. In between, a minimum time trajectory, which avoids Cb areas according to the considered forecast data at the entry point, is calculated (see Figure 2, blue trajectory) using the cost functional shown in equation (1). The resulting flight time and fuel burn is compared to the reference trajectory (see Figure 2, red trajectory) and the great circle trajectory (see Figure 2, black trajectory) which represents the optimal route in terms of flight distance, fuel burn and flight time. For all trajectories, a constant mach number and a constant flight level is assumed. An additional assumption is to neglect traffic conflict avoidance based on the fact, that the south Atlantic airspace is a low-density airspace. By using data from the European Centre for Medium Range Weather Forecast (ECMWF) the wind impact was checked for each of the optimized flights, and it turned out that for all these flights the head wind component was neglectable.

Range of potential fuel savings

We present trajectory optimizations for three of the 75 identified IAGOS flights with Cb avoidance manoeuvers. They are listed in table 2. The first two flights show major deviations of more than 60 minutes. They have been chosen to estimate the maximum of fuel saving potential because they represent the most extreme avoidance manoeuvers. The third flight shows only a minor deviation which took about 20 minutes. This flight has been chosen in order to demonstrate a case where an avoidance manoeuver was actually not necessary, and would not have been flown, if the pilots would have had Cb-global on-board showing them an overview and a nowcast of the situation.

Table 2: Optimized IAGOS Flights

IAGOS flight name	Date	Location of deviation	Duration of deviation [min]	Max. fuel saving [t]
2013020323583403	03.02.2013	Central Atlantic	75	3.3
2014033022413907	30.03.2014	North-East Brazil	60	1.3
2014041910001507	19.04.2014	Central Atlantic	20	0.206

The flight on 3 February 2013 is the flight that has already been discussed in Forster et al., [2017] to show the added value of Cb nowcasting for flight safety. It departed in Rio de Janeiro on 3 February 2013 at 23:58 UTC, arrived in Frankfurt on 4 February 2013 at 11:41 UTC, and reached a line of Cbs over the central Atlantic at about 3:15 UTC on 4 February 2013. Figure 3 illustrates the Cb detections (red and orange contours) and 30 minutes nowcasts (dashed contours) for this flight on 4 February 2013 at 02:15 UTC together with the original flown route (pink line) and the TOM optimised route (green line) between the entry and exit point of the Cb-global tile. The TOM optimised route was calculated on the basis of the Cb-global 60 min nowcasts of 02:15 UTC which is about the time when the aircraft entered the Cb-global tile at its southern border. Thereby it is assumed that the optimized route returns to the original route at the exit point of the Cb-global tile. The optimization results in a fuel saving of approximately 3.3 t compared to the fuel consumption of the original flight. This is considerably more than the approximately 2 t of fuel savings the pilot had estimated in his post-operational analysis [Forster et al., 2017] and reflects the potential of the usage of trajectory optimization tools in combination with nowcasting information. In Forster et al. [2017] the pilots started to use Cb-global data quite late, i.e. when they were already on their avoidance route around the Cbs. Obviously, the fuel saving potential is the higher the earlier the Cb-global information is used to adjust the flight route.

In the second case on 30 March 2014 the aircraft departed in Rio de Janeiro at 22:41 UTC, arrived in Madrid at 8:05 UTC on 31 March 2014, and avoided a Cb over north-eastern Brazil at around 00:30 UTC. The original flown route avoids the Cb on its western side (Figure 4, pink line). However, based on the Cb-global nowcasts which indicate a movement of the Cb to the west, the TOM optimization suggests a deviation on the eastern side of the Cb (green line). The optimized avoidance manoeuver starts at the entry point into the Cb-global tile about one flight hour before the Cb was reached. It is based on Cb-global detections and nowcasts at 22:45 UTC shortly after take-off, i.e. about 90 minutes before the original detour was initiated by the pilot (Figure 4). The optimized route returns to the original flight path at the exit point of the Cb-global tile, and the fuel saving potential amounts to 1.3 t in this case. A second TOM optimization of the same flight using Cb-global information at 23:30 UTC revealed only 0.66 t of fuel savings confirming the conclusion that the fuel saving potential is the higher the earlier the Cb-global information is used to adjust the flight route.

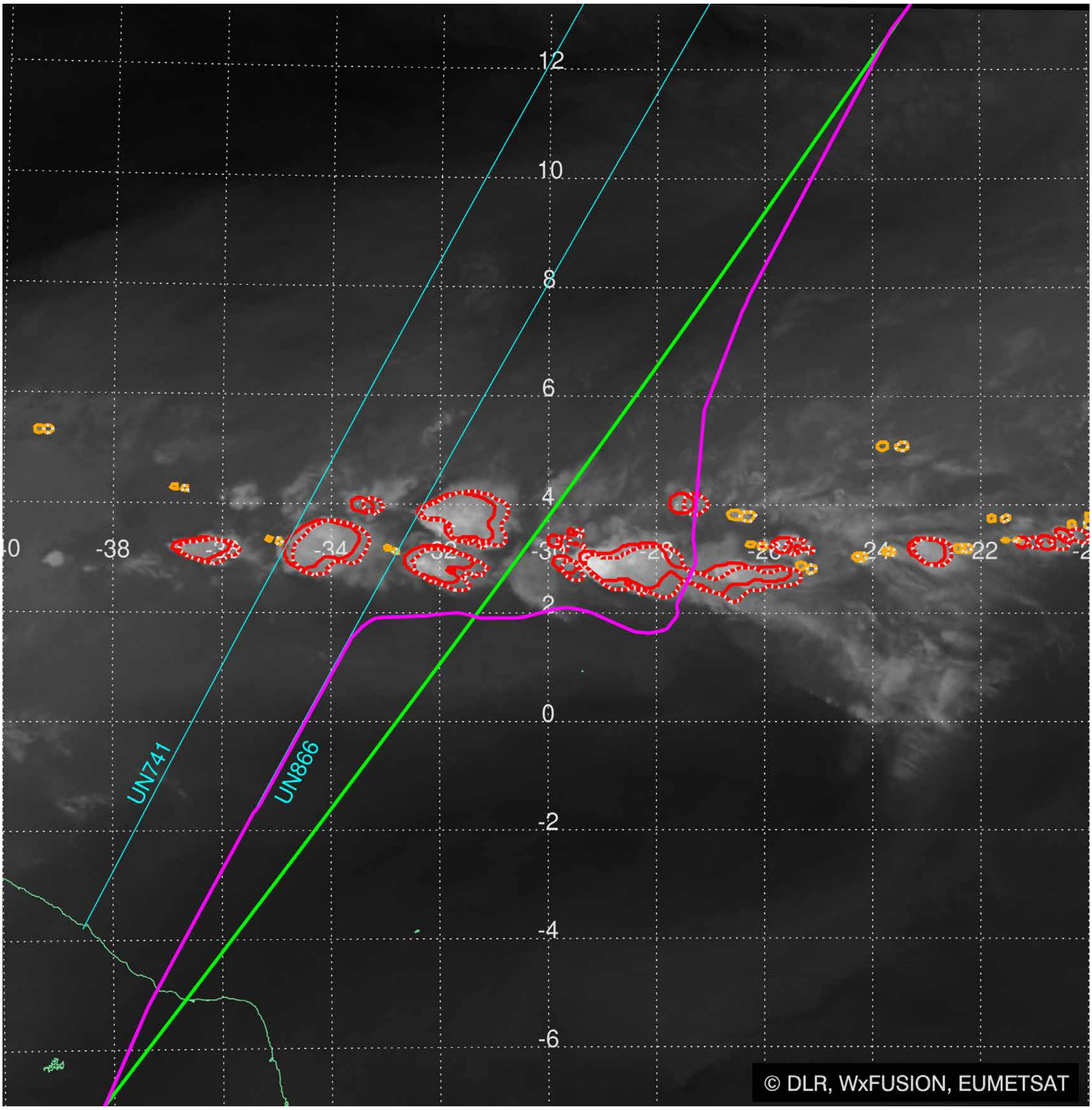

Figure 3: Trajectory optimization with TOM based on Cb-global on 4 February 2013 at 02:15 UTC (METEOSAT satellite image in the background).

The third flight on 19 April 2014 departed in Madrid at 10:00 UTC, arrived in Sao Paolo at 20:50 UTC, and flew an avoidance manoeuver over the Central Atlantic starting at around 16:15 UTC. The Cb-global detections and nowcasts at 16:00 UTC (Figure 5) show that the Cb cells tend to move westwards, and that it would have been smarter to pass by the Cb on its eastern side. In fact, an avoidance manoeuver (pink track) was actually not necessary, and the fuel saving estimated by TOM would have been 0.206 t, if the aircraft would have continued on its planned track which is the optimum track in this case (green track).

It can be concluded that Cb-global does not only enable safe and efficient strategic flight planning around Cb cells, but it also enables the pilots to optimize their precautionary measures.

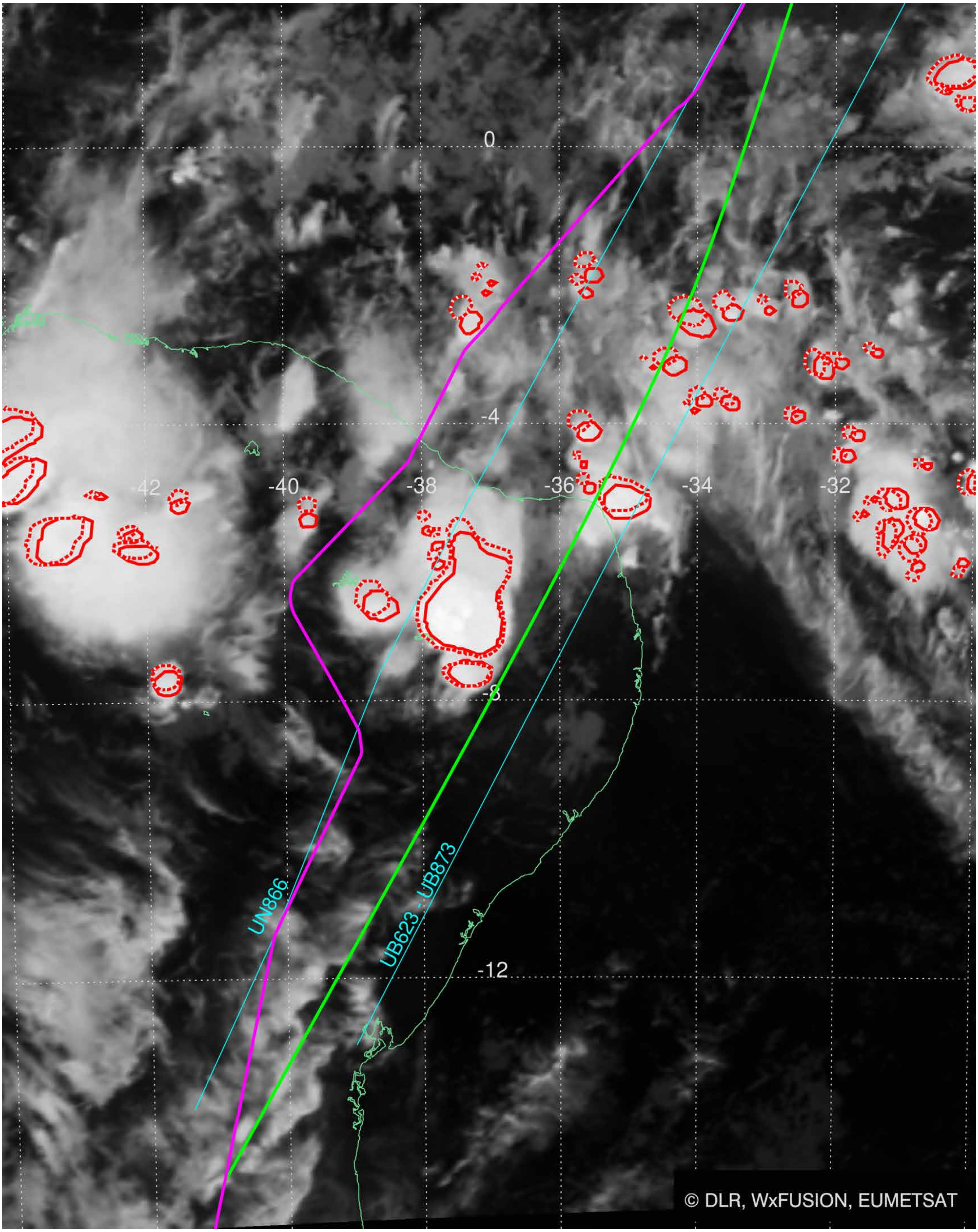

Figure 4: Same as Figure 3, but for the flight on 30 March 2014 based on Cb-global detections (bolt contours) and 30 min. nowcasts (dashed contours) at 22:45 UTC

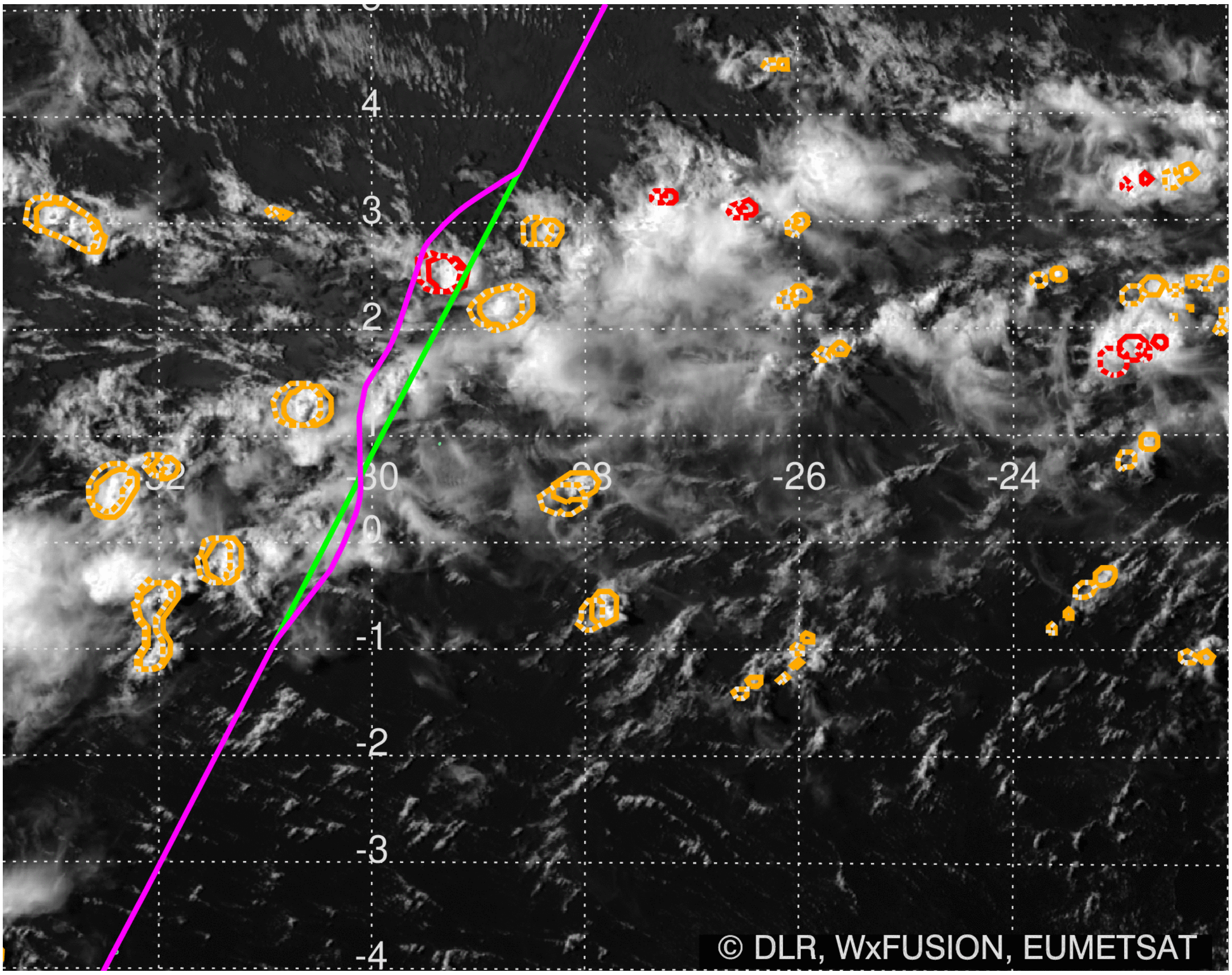

Figure 5: Same as Figure 3, but for the flight on 19 April 2014 at 16:00 UTC.

Discussion

The statistical approach and, thus, the results obtained by approach 1 are based on several assumptions. Nevertheless, our estimate of 0.548 t per flight compares well to previous studies like Enge et al. [2014] and Kim et al. [2015] and seems to be somewhat more conservative than these studies: In flight tests between New Zealand, Japan, and China Enge et al. [2014] obtained 0.616 t of fuel savings per flight, if the most up-to-date information about wind and convective weather information is used for the planning. The study by Kim et al. [2015] revealed 0.716 t of fuel savings per flight crossing the Continental U.S., if combined wind and convective turbulence forecasts are accounted for in the flight planning. We are therefore confident that our estimate is realistic and representative not only for the ITCZ over the Central Atlantic, but also worldwide.

Our results indicate that the planning based on Cb-global data generally enables fuel savings over the Central Atlantic. The fuel saving potential is the higher the earlier the Cb-global information is used to adjust the flight route. However, one has to keep in mind that Cbs are quickly developing phenomena, and Cb information for more than one hour beforehand should rather be used as a pre-warning. A route adjustment planned and initiated more than one hour beforehand might not be reasonable, because of newly developing Cb cells. In contrast, for a planning horizon up to 60 minutes the overview of the situation and the nowcasting provide a basis for route adaptions resulting in a clear benefit. This is also confirmed by the development and westward movement of the avoided Cb in Figure 4 which was nowcast by Cb-global and shows that an avoidance manoeuver on the eastern side of the Cb would most probably have been smarter both from a safety and efficiency point of view.

The trajectory optimization used here is based on assumptions e.g. the defined starting and ending points of the trajectory segment to be optimized, which are the crossing points of the given trajectory with the Cb-global tile. The avoidance manoeuver is solely based on the Cb situation observed and nowcast before or at the entry point of a Cb-global tile, and no updates were used to continuously adjust the optimum route afterwards. In reality, a pilot would probably choose an avoidance route close to the typical airways over the Atlantic, and the start and end of an avoidance manoeuver is certainly dependent on the individual decision of the pilot. Different pilots would probably make different decisions in the same situation. It is therefore clear that in reality the fuel saving potential strongly varies from flight to flight. Keeping this in mind and keeping in mind the fact that in the test flight from the study by Forster et al. [2017] 2.0 t could have been saved, we are confident that a maximum fuel saving potential up to 3.3 t revealed by TOM is still realistic.

The results presented here are only representative for en-route flights outside of complex air spaces like Europe. En-route, e.g. over the Central Atlantic ocean, the pilots are relatively free in their choice of the flight route, and normally air traffic control can give clearance for most of the flight route adjustments, because conflicts with other traffic are rather rare. However, due to the high density of flights in the European air space conflicts with other air traffic have to be resolved and prioritized for the planning of flight manoeuvers around Cbs. For complex air spaces, the fuel saving potential might therefore differ from that for an en-route scenario. Whether it is on average higher or lower is not straight forward to estimate and subject to further investigations. On the one hand, avoidance manoeuvers cannot freely be chosen, and might therefore not be as efficient as in the case of an en-route avoidance manoeuver. On the other hand, the use of Cb nowcasting in dense air spaces can result e.g. in less holding patterns in Terminal Manoeuvring Areas and less landings at alternates and consequently in reduced fuel consumption.

Conclusion

In summary, we come to the following conclusions:

1. The results suggest that the flight planning based on Cb-global data generally enables fuel savings.
2. The fuel saving potential is the higher the earlier the Cb-global information is used to adjust the flight route.
3. An average fuel saving potential of 0.548 t per flight for the flight routes over the tropical Atlantic is conservatively estimated, if up-to-date Cb-global information is available and used for the planning of flight adjustments. This would result in a positive financial effect for an airline comparable to or even higher than other fuel efficiency projects already implemented.
4. A fuel saving potential of up to 3.3 t has been calculated for a flight with the most extreme deviation around Cbs out of 75 selected IAGOS flights, if Cb-global information is used for flight route optimization with TOM.
5. Although the two approaches presented in this study are independent from each other, the fuel savings revealed by both approaches are within a realistic range and comparable to numbers obtained in previous studies.
6. Pilots can improve their operational precautionary measures during flight by using the Cb-global information. A case has been presented where a deviation around a thunder cell was not necessary and could have been avoided, if the overview and the nowcasting with Cb-global would have been available.

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Mitigating the climate impact of non-CO_2 emissions: EUROCONTROL MUAC live trial 2021

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Abstract

With two-thirds of aviation's climate change impact believed to come from aircraft non-CO2 emissions, contrail prevention has a key role to play in the mitigation of the climate impact from aviation. EUROCONTROL's Maastricht Upper Area Control (MUAC) is conducting contrail prevention in a live trial during 2021. This contrail prevention trial is the first of its kind in the world, and will investigate the operational feasibility of contrail prevention by ATC and evaluate its impact.

The trial is assessing how to avoid warming persistent contrails with eco-efficient flight trajectories in live operations. MUAC is examining relatively minor operational measures such as small flight level changes, for example diverting aircraft 2,000 feet up or down from their normal flight path, to reduce persistent contrail formation and contrail cirrus. This requires creating a contrail prevention system, implementing operational procedures for contrail prevention, and the validation of the methodology with satellite image analysis by the project partner DLR.

Ensuring a positive environmental balance between reducing greenhouse radiation effects whilst potentially increasing CO2 and other environmental pollutants is a challenge of the trial, in order to fly environmentally optimal flight profiles. This demonstration shows which practical difficulties have to be overcome if we are to implement ATM procedures to reduce the climate impact of aviation, and whether today‘s meteorological tools are good enough at forecasting areas where persistent contrails tend to form, and which should be thus avoided.

Introduction

MUAC in numbers

The Maastricht Upper Area Control is an international non-profit civil military integrated air traffic control provider, operated by EUROCONTROL on behalf of the Four States – Belgium, Germany, Luxembourg and the Netherlands.

The area of responsibility of MUAC, more than 260,000 km2, consists of the Brussels UIR (Upper Information Region), the Amsterdam FIR and the Hannover UIR from flight level 245 to flight level 660. Some 1.9 million flights pass through MUAC's area of responsibility each year, making it the third busiest air traffic control facility in Europe in terms of traffic volume. During the summer, peak days see over 5,700 flights. Over 17% of all European flights use MUAC's airspace (pre-Covid figures).

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The MUAC area of responsibility is a complex and dense airspace in the close vicinity of major airports, including Amsterdam, Brussels, Copenhagen, Düsseldorf, Frankfurt, London and Paris. MUAC interfaces with a large number of civil and military area control centres and upper area control centres.

This busy and complex airspace is managed by about 750 employees from 29 nationalities. MUAC is organised on a multinational, civil-military and cross-border basis and this is a perfect example of the simplification and harmonisation of airspace in Europe and is fully in line with the objectives of the Single European Sky.

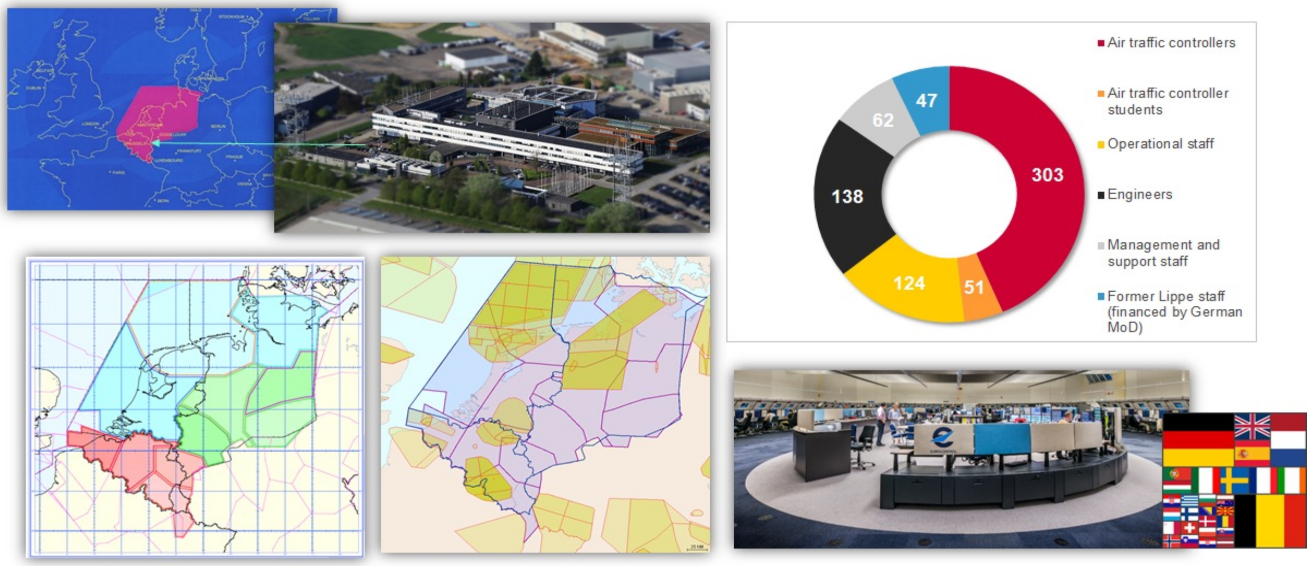

Figure 1: EUROCONTROL Maastricht Upper Area Control (MUAC).

Climate change, non-CO2, ISSR and contrail cirrus forcing

A nice introduction to contrail and contrail cirrus can be found in [2], and is cited here with some shortening:

“A substantial component of aviation’s climate impact is presently caused by non-CO2 effects, most notably contrail formation; if weather conditions are right, these can evolve into so-called contrail cirrus. A recent assessment of the drivers of climate change due to aviation estimated the present-day climate effect of contrail cirrus was 65-70% greater than that of CO2, albeit with a significantly greater uncertainty. Clearly, if that contribution could be mitigated, it would be highly desirable. […]

To understand the issues, we need to […] distinguish between contrail types (see Figure 3). Initial contrail formation is relatively easy to predict, from knowledge of the temperature and humidity of the engine exhaust and the temperature and humidity of the surrounding air. As the engine exhaust mixes with the surrounding air a familiar, but peculiar, phenomenon can occur. When two unsaturated air masses mix together, they can form a saturated air mass, allowing a cloud to form; the physics is similar to what causes us to see our breath on a cold day. In the case of contrails, one difference is that soot particles in the exhaust provide the particles on which water vapour can condense.

Such so-called ‘condensation nuclei’ are abundant in the lower atmosphere but much less so at cruise altitudes, a fact important to our later discussion. Another difference is that the droplets almost instantaneously freeze, due to the cold temperatures. Just as the clouds from our breath dissipate quickly, so contrails often only last a few seconds. As the engine exhaust mixes with the surrounding air, it is diluted to such an extent that the cloud particles evaporate (or strictly sublimate from ice to vapour). These short-lived contrails are insignificant from a climate perspective.

Less commonly, but still quite frequently, the surrounding air at cruise altitude is ‘ice saturated’. This means it contains enough water vapour that, if there were sufficient quantities of the right kind of nuclei (‘ice nuclei’), a cloud would form. However, in the clean air at cruise altitudes there are often not enough such particles, and such regions are called ‘ice supersaturated regions’ (ISSR). If an aircraft flies through an ISSR, and conditions are right to form short-lived contrails, then the ice particles in contrails are ideal sites for the ‘excess’ water vapour in the air to condense on. Instead of sublimating, the contrail grows and persists. Line-shape or persistent contrails are a frequent sight over, for example, the UK. A useful definition is they are contrails that persist after the aircraft causing them is no longer visible and this occurs on a timescale of a few tens of minutes.

Persistent contrails can further spread out so that, to the naked eye at least, they appear little different to natural high-altitude cirrus clouds and can persist for many hours. We call these (together with the persistent contrails) ‘contrail cirrus’. It is these that contribute to aviation’s climate effect. A complication is that ISSRs are primed for natural cirrus formation and the formation of contrail cirrus acts to slightly reduce the amount of natural cirrus that would otherwise form. This is an area of active ongoing research but recent calculations indicate that this effect reduces the effective climate impact of contrail cirrus by more than half; this is taken into account in the recent estimates of aviation’s total climate impact.”

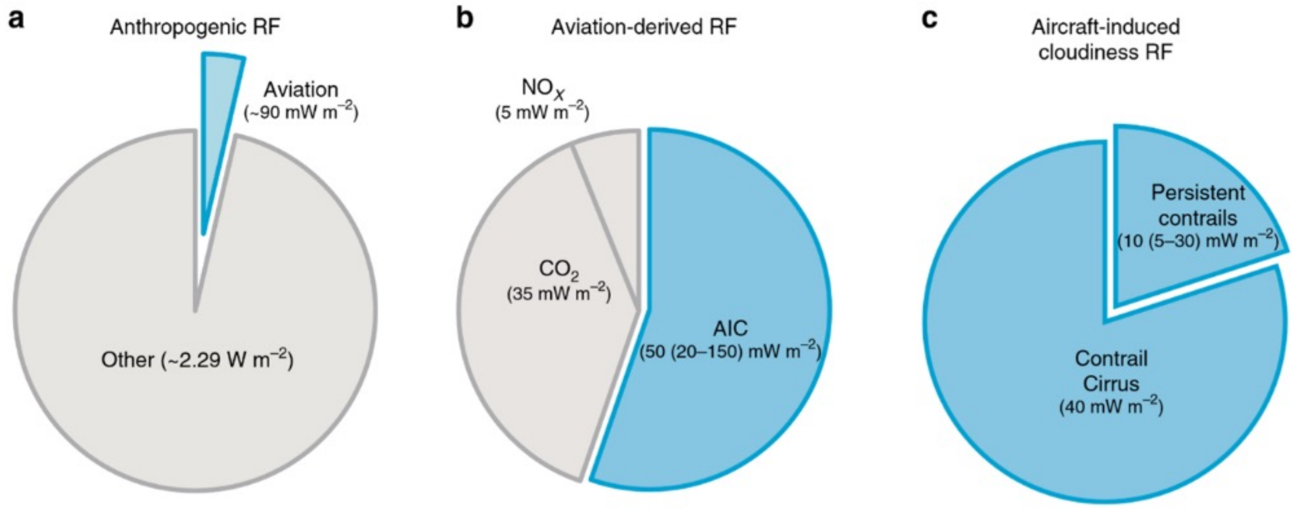

Figure 2: Aviation radiative forcing components. [a] Aviation as a percentage of total global radiative forcing (RF) due to human activities in the year 2011 relative to pre-industrial times. [… (about 4%) …] [b] Forcing components within the aviation fraction, of which aircraft-induced clouds (AIC) account for more than half […] [c] Breakdown of AIC radiative forcing into contrail cirrus and persistent contrails […].[1] The figure should be used with caution, since there are high uncertainties especially about the non-CO2 effects on radiative

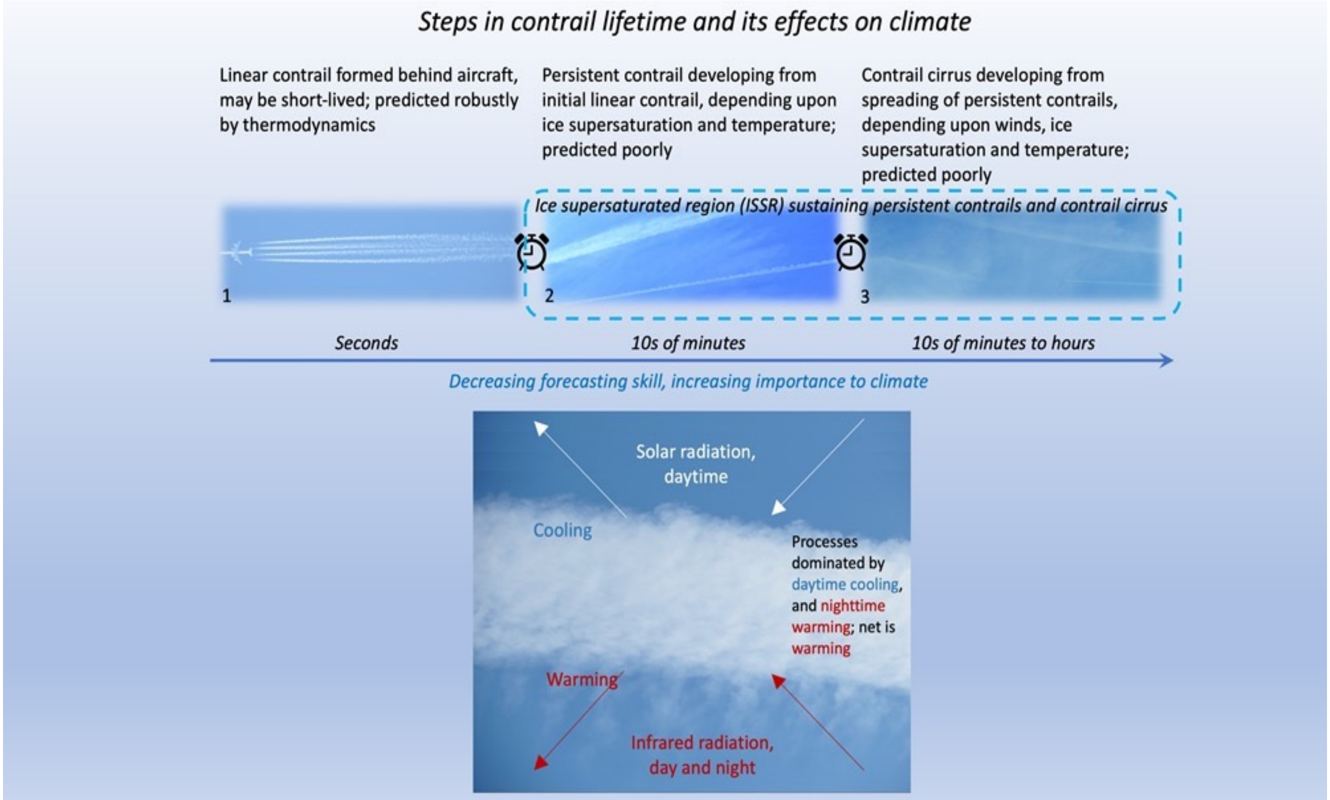

Figure 3: Illustration of different types of contrail and the radiative forcing, which causes the climate effect.[2]

Objective of the trial

Operations at Maastricht UAC have a long tradition on working on environmental tasks. Up to now fuel optimal solutions were centric, e.g., MUAC was at the origin of the European direct route network. The contrail prevention trial was kicked off in 2020 and is about the non-CO2 effects. MUAC's objective is to evaluate the feasibility of preventing contrail and contrail cirrus, which are most probably very high contributors of aviation to the climate change, see [1]. The MUAC trial for contrail prevention evaluates two objectives in 2021:

- the technical feasibility for contrail prevention and the accuracy of ISSR forecast.
- the operational feasibility for vertical contrail prevention at traffic loads.

A video of the trial objectives can be viewed in [3].

Partnering with DLR

MUAC is partnering with the DLR (Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany (https://www.dlr.de/pa/)). The DLR has a very long history in research of contrails and the climate effect, and is contributing with their know-how about the physics of the atmosphere, the modelling of contrail and contrail cirrus, and satellite image analysis to evaluate the success-rate of contrail prevention.

The Trial

Operational concept options

There are different options for concepts of contrail prevention by circumnavigation of ISSR:

- Pre-tactical flight planning: Assuming the prediction of ISSR can be made accurately with a longer time horizon, flights can be planned to circumnavigate horizontally or vertically the ISSR. The advantage is the plannability, and herewith the possibility to compute against a variety of variables to achieve the environmental or economical optimal flight profile. The disadvantages come with the skill of the ISSR prediction: If not high, then either the contrail prevention is not well performing and needs very high buffers, or is even counterproductive, and will in most cases lead to higher fuel burn and herewith higher CO2 emissions. Further, strict vertical plannability in high density areas like MUAC is very difficult to achieve.
- Tactical pilot decision: Assuming the aircraft has a means to detect ISSR, it could trigger the (vertical) circumnavigation to avoid ISSR. Upon detection of ISSR in the avionics, the pilot would report ISSR and request flight level change, or execute procedure. This concept is most powerful, because it could be operated everywhere on the globe disregarding the technical and operational abilities of ATM, and is potentially very precise, and the pilot could decide on the flight optimal circumnavigation. Unfortunately, at the time of editing the paper, the avionics to detect ISSR are very rare, not validated or precise enough, and international procedures for

pilot-initiated ISSR avoidance are not existing. It would have high cost for avionics equipment of high percentages of the fleet. The concept is hardly to work in high density traffic.

- Tactical ATC decision: Vertical circumnavigation of ISSR initiated by Air Traffic Control (ATC). The advantage is to be potentially more accurate with lower additional fuel burn, and hence less additional CO2 [4]. The risk of being counterproductive is low, provided there is a real-time feedback system in place. The concept might work in high density traffic, up to a to-be-found threshold beyond which contrail prevention is not possible anymore or the airspace needs regulation.

It can be imagined that there will be a mixture of all three concepts: planning for airline optimisations and provision of ATC capacity, pilot tactical decisions for operations around the globe with minimised additional fuel burn, and tactical ATC decisions for high density airspace.

Detailed operational concept and daily process

The trial has been communicated to the aviation community by AIC (Aeronautical Information Circular). During the contrail briefing, members of DLR, MUAC supervisors and the project team analyse ISSR predictions per sector thoroughly, identifying potential time periods, areas and levels where ISSR conditions are likely to be present, and then advise to Operations, which levels should be avoided. The briefing for contrail prevention takes place at 1600 UTC every other day, with a forecast for the following 6 hours. It has been decided to perform contrail prevention in the evening and night only as the impact on the environment of contrail cirrus is considered worse in the evening and night time. This has the additional benefit of lowering the impact of the trial on operation and impact on the airlines is kept to a minimum.

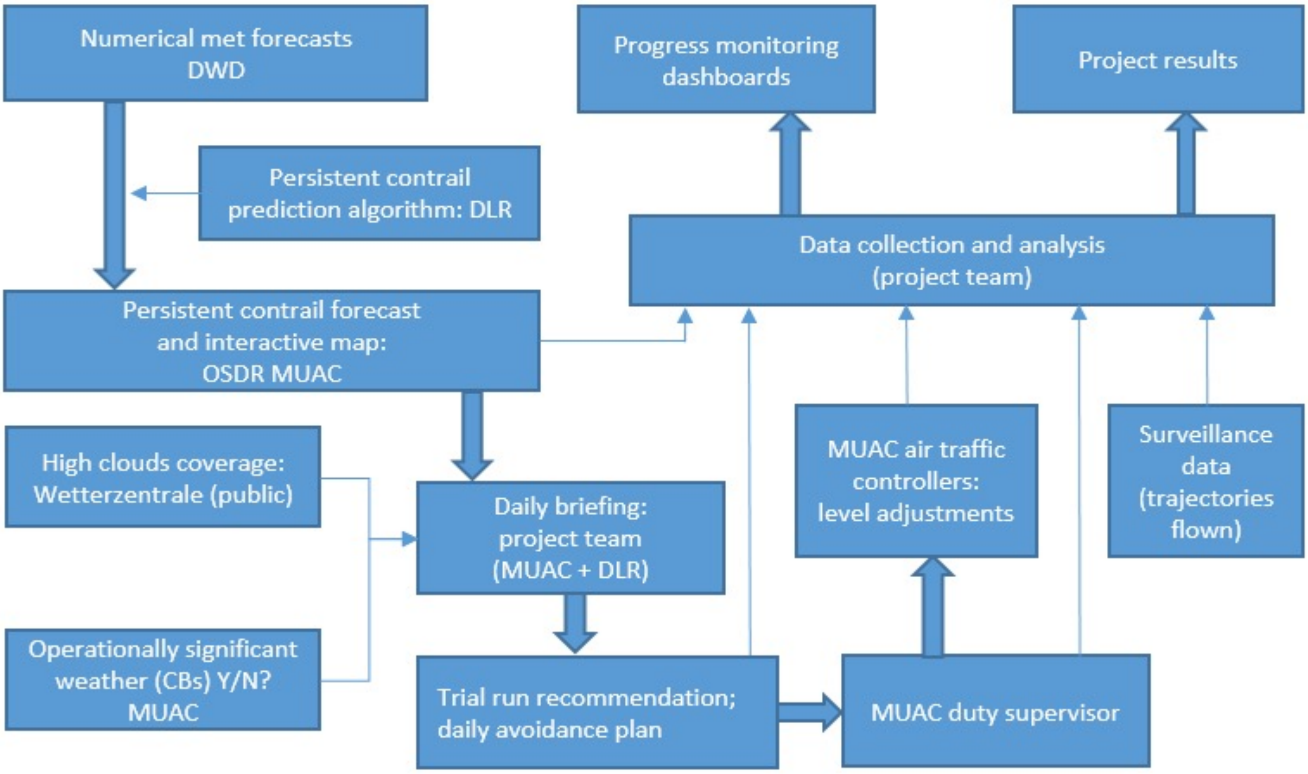

Figure 4: Trial Execution Workflow.

The Executive Duty Supervisor (eDSup) will determine if the operational situation on the sector allows for the conduct of the trial and under what conditions. The supervisor's decision making is influenced by:

- The weather forecast, ongoing or expected weather events such as CBs or turbulence. Deviations in the horizontal and vertical plane are frequent during these circumstances and the resulting extra workload and requests for additional deviations need to be avoided.
- The traffic levels and complexity: Capacity issues as during periods of high traffic there is no additional spare time to provide additional instructions and eventual explanations as to the reason for the level changes. At the same time, traffic can be condensed in such a way that there is a need to occupy all available levels.
- High density military exercises due to the blockage of large parts of the airspace together with increased coordination workload.
- On-the-job training, though can be accepted if the coach agrees.
- Ongoing or planned system activities which mean increased workload at sector level

The final decision of the trial to go ahead is with the eDSup (Executive Duty Supervisor). If the supervisor can approve the trial to go ahead, they will pass a table containing relevant information (sectors, times and level bands to be avoided) to the controllers. The supervisors ensure that safety of flights is never impaired by contrail prevention at any time.

ATCOs are aiming to keep aircraft in level flight out of predicted areas of ISSR by issuing climb or descend clearances by not more than 2000 feet. Route deviations level changes by more than 2000 feet to leave ISSR areas are out of scope of the trial. Aircraft with requested cruise altitude above or below levels of ISSR prediction can be cleared through ISSR in climb or descend preferably with a high climb- or descend rate. Departing aircraft within our area of responsibility with requested cruise altitude in ISSR prediction are kept below requested altitude on average for 10-15 minutes. Arriving aircraft may be descended early.

ISSR prediction is usually rather stable in height within a weather system which helps the controller to execute contrail prevention as it is plannable. The phraseology used for contrail prevention is “Due to contrail prevention climb/descend FL XXX.” Aircraft that have been deviated for contrail prevention reasons are marked with “WX”. This input makes the analysis of the trial possible offline.

Detailed technical setup

During the trial, MUAC relies on a persistent contrail prediction algorithm prepared by DLR (German Aerospace Centre). The algorithm was implemented by MUAC, as a part of existing internal application called OSDR (Operational Support Data Retrieval). The input data is retrieved from the 12-hours numerical weather forecast provided by DWD (Deutsche Wetterdienst) in a netCDF format, updated 4 times a day, at predefined hours. Only the first 6 hours of each forecast are used during the trial. The original data from the DWD model levels is linearly interpolated to obtain the missing cruising flight levels. The outcome of the prediction is visualised as an interactive map, which shows the evolution of the affected areas and flight levels over time. To present the areas to avoid in a form of a map, it was required to assume a constant value for the averaged jet engine coefficient. The selected value – 0.4 – was selected taking into account typical aircraft types cruising in the MUAC airspace of responsibility. Depending on the results, a different approach can be proposed in the future to improve the accuracy.

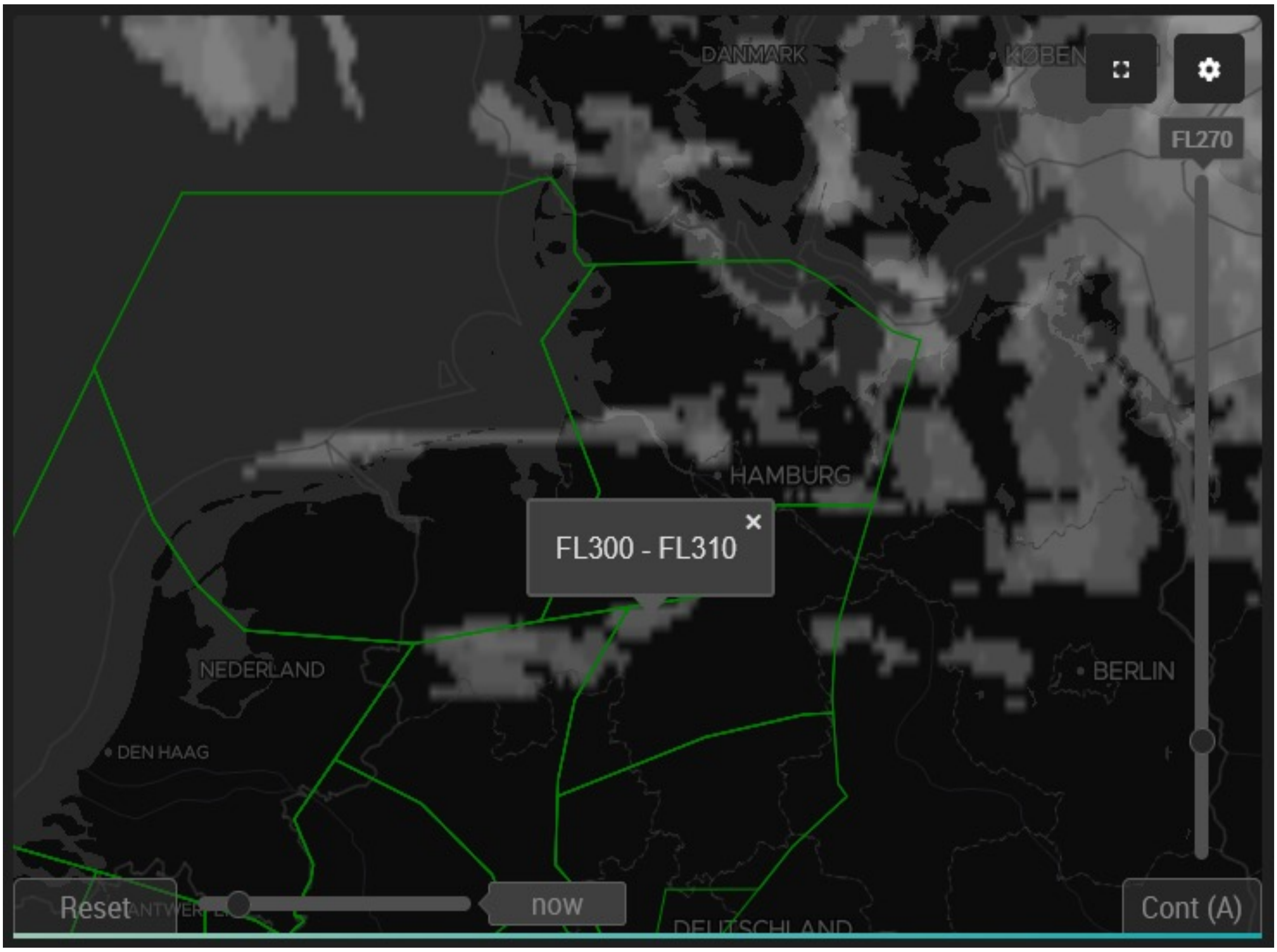

Figure 5: Sample picture from MUAC OSDR application, showing expected areas where contrails are likely to be created.

Initial findings

Counts and methods

To monitor the project progress, and to assess the project impact on operations, MUAC collects the following data for further analysis: surveillance data - flown trajectories (ASTERIX format plus XML pre-processed data), numerical weather predictions of the areas where the persistent contrails are expected, together with their corresponding input data (netCDF), daily yes/no decisions and daily avoidance plans from the project team (originally in Excel, automatically imported to Oracle/Tableau), the list of flights marked by air traffic controllers as deviated for contrail prediction (CSV displayed in Tableau), and some qualitative feedback from air traffic controllers and supervisors (surveys). Some of this data is daily visualised in a form of dashboards, to let the project team monitor the execution of the plan, and to be able to respond to anomalies. The data is also shared with DLR for the purpose of validation of the trial outcome.

To reduce the workload of air traffic controllers, the project team prepares specific avoidance plans for each trial run, to make sure that controllers do not need to continuously cross-check prediction maps.

The plan is a combination of times, elementary sectors and flight levels to avoid. These daily plans also feed the progress monitoring dashboards. MUAC keep a trace of the trajectories still crossing the areas recommended to avoid, the percentage of traffic which crosses these areas in relation to the total traffic crossing MUAC airspace in this period.

The daily avoidance plans are constructed using elementary air traffic control sectors as the building blocks. In some cases, especially in the northern part of MUAC area of responsibility, a single sector is big enough to be only partially covered by ISSR layer. In such case, avoidance decision is taken by the project team based on the proportions of the ISSR size to the sector size. The numbers of flights deviated and flights still crossing ISSR are based on the airspace selected in the avoidance plan, not the actual ISSR shapes and sizes.

Controllers make special inputs in the system, to indicate that given flight profile was adjusted because of the trial. It is not an accurate way to count it (some flights were initially tagged with the input, but finally not deviated), but it helps to monitor the efficiency of the avoidance – i.e. to check if controllers are able to still pursue the trial goals. Avoiding instructions are issued on a best-effort principle, and only if it does not interfere with primary tasks of air traffic controllers.

Numbers

The trial is still in progress – presented numbers refer to 23 August 2021.

The traffic at the beginning of the year was extremely low and it is gradually recovering. Additionally, one of the prediction parameters was fine-tuned after the start of the trial (ISSR threshold reduced from 1.00 to 0.98). For these reasons, the numbers from the first months of the trial should not be directly projected to the remaining part of the year. Because of the low traffic numbers so far, it is too early to make statements about the operational feasibility of performing such a contrail avoidance in the future.

Since February, trial runs are normally executed on every odd day, in the afternoon. So far, MUAC has executed a trial run 61 times. A trial is skipped when the optical thickness of high clouds is too high to be able to analyse results using the satellite imagery. It can also be skipped if there are significant CB clouds in the area, forcing aircraft to deviate from their planned routes to avoid adverse weather. Each decision is documented and logged.

So far, controllers indicated level changes to prevent contrails for 158 aircraft. The actual effectiveness of the trial – the impact on cloudiness - will be independently evaluated using the satellite imagery.

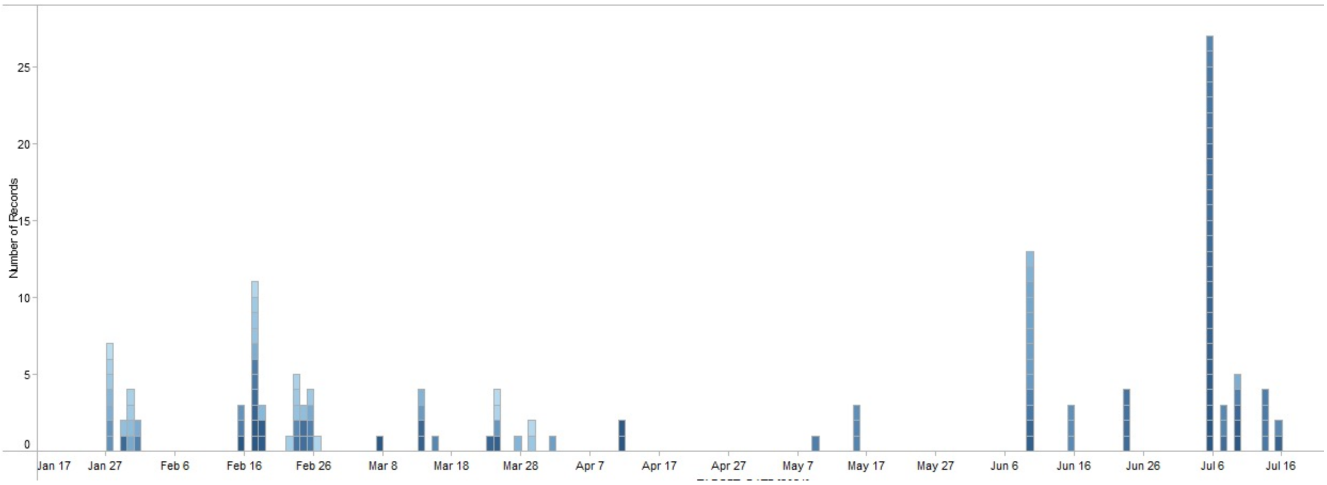

Figure 6: Number of flights deviated daily during the trial.

During the trial run, contrail prevention is only achieved by adjusting vertical profiles and by no more than 2000 ft. Crossing the avoided region in climb or descent is unrestricted. So far, 3622 flights were identified as crossing the areas indicated in the daily avoidance plans, which is around 2.5% of all flights crossing the airspace in this period. Around 70% of the flights crossing ISSRs significantly changed altitudes in MUAC sectors, climbing to their cruising levels or descending to destination aerodromes.

MUAC does not calculate the impact of the executed tactical manoeuvres on a fuel consumption case by case. Generally, expected impact of a temporary deviation of 2000 feet at a cruising altitude is relatively low, but the accurate calculation would require additional details about every specific flight. Some factors to consider are listed below. Filed levels from the flight plans do not always perfectly match with optimum altitudes. If the flight is planned and conducted below its optimum altitude (for example because of the independent ATC constraints) – a descent of 2000 feet will typically have a greater effect than descending 2000 feet from the optimum altitude. The optimum altitude gradually moves higher as the flight progresses, as the aircraft gets lighter. Changing the level at the later stage of the flight is less penalising than right after departure. Depending on the distance to TOD point (TOD - Top of Descent), pilot may prefer to stay on the new level rather than climb back to the original one. There may be a delta in a wind or temperature in the new level. The impact of level deviations differs between aircraft types, and even among the aircraft types sharing the same ICAO aircraft type designator.

Stakeholder reactions

Launching the trial raised a lot of interest not only from the airlines, but also from other entities such as: ANSPs (Aeronautical Navigation Service Providers), aircraft manufacturers, pilots´ association, individual pilots, meteorological services providers, government officials, flight planning software developers, as well as from IT companies looking for commercial opportunities. The overall response from the airlines was very positive. Only one airline refused to participate in the trial, arguing that their policy requires to cut all potential cost during the COVID crisis. Our impression from many, if not most airlines is that they share the strategic importance of the topic and offer to cooperate in finding mutually acceptable solutions.

Challenges

The weather and the traffic in 2021

Subjectively, the weather in the MUAC area in 2021 was very bad. Meteorologist might confirm this later, but we see from our daily observations for the ISSR prediction that from January until August 2021, the date of editing this document, there was constant rainy cyclonic weather, cyclones at short intervals with the effect of very short durations of ISSR, and it was cold and hence ISSR at low altitudes. We hardly had the typical longer duration anti-cyclonic weather with longer lasting and stable ISSR.

The traffic rates in 2021 were very low due to COVID, a bit more normal in the night due to the higher proportion of cargo flights, but there was clearly less traffic during the day. This was helpful in the introduction of contrail prevention for operations, but lowered the probability of flights passing through ISSR.

ISSR prediction and detection

MUAC is locally computing ISSR, based on the predicted temperature and relative humidity from the ICON weather model from DWD as explained above. This system was slightly tuned during the trial, and some effort was invested to have a verification loop for the ISSR prediction with visual observations from pilots and on the ground; however, this is not satisfactory. More effort is needed to build a solid and verified ISSR prediction, using frequent measures of Relative Humidity (RH) in aircraft, and an automatic contrail detection for constant feedback.

Outlook

Requirements for technical system improvements

There is a substantial need for new and improved technical systems:

- ISSR prediction: The weather forecast needs improvement for ISSR prediction.
- Persistent contrail and aviation induced cloudiness: Weather models are needed to evaluate usefulness of the contrail prevention in the specific weather context regarding other clouds or natural cirrus or the stability of the weather system, etc.
- ISSR detection with Relative Humidity (RH) sensors with data link: If the sensors for RH prove to work well at high altitudes and in cold air, then high equipage rates should be targeted in combination with datalink. This could be the main enabler for world-wide ISSR detection and contrail prevention.
- Real-time contrail detection with satellite: For an instantaneous feedback loop there should be a real-time satellite contrail detection system with high resolution. For northern Europe e.g., this would require higher resolution than the next generation GEO satellites and higher update rates than current generation LEO.
- Real-time contrail detection with ground-based cameras: Relatively simple ground-based camera networks with contrail detection can give immediate feedback, for the portion of contrails that can be seen from the earth surface through low clouds in the vicinity of the cameras.

Estimates on climate impact

The objectives of the MUAC trial in 2021 are limited to the technical and operational feasibility of contrail prevention by tactical ATC measures. We do look at eventual additional CO2 emissions; however, to evaluate the impact of contrail prevention on the climate change [5] was not part of the objectives and we have not worked on this. Next project stages should incorporate the so-called Climate Change Functions [6], or Environmental Change Functions [7], and then gradually look into environmental optimal flight profiles, including more factors than contrail and CO2.

That will require multiple efforts from aircraft manufacturers, airline operators, air traffic management, and air traffic control.

Political

In terms of comparing aviation CO2 emissions with non-CO2 emissions and their impacts on a common scale, equivalent emissions metrics are required (CO2-e). The Global Warming Potential for a time-horizon of 100 years (GWP100) metric is widely applied as the CO2-e.

Formulating aviation emissions equivalencies for short-lived climate forcers i.e., non-CO2 impacts with the long-lived greenhouse gases (CO2, methane, etc.) presents scientific and policy challenges. In addressing this, the scientific community has proposed a number of alternatives to the GWP100.

There is no exclusively ‘correct’ choice of a CO2-e metric, as the choice depends on the policy, e.g., temperature target, emissions reduction target, and also on the subjective choice of time horizon of interest. A particular challenge is associated with the use of emissions metrics to assess policy options that involve a reduction of a short-lived climate forcer with a possible CO2 penalty.

Any mitigation measures will almost certainly have a negative impact on airlines cost-efficiency, so they should be given thoughtful consideration beforehand.

Regarding ATC, the trial team is counting the proportion of flights that are successfully circumnavigated above or below the ISSR. The part of flights that is crossing ISSR is analysed and missed flights are discussed. This operational metric can eventually evolve into a key performance indicator (KPI) for ATC units like other cost or delay. However, we do not recommend any penalisation because ISSR avoidance is not synonym with contrail prevention, or with prevention of aviation induced cirrus clouds.

From our current level of experience, it seems difficult to make a backwards tracing of one specific aircraft that generates one contrail to an induced cirrus cloud and hence the polluter-payer principle might be difficult to track and doubtful to apply.

Summary

EUROCONTROL Maastricht UAC conducts the worldwide first live trial for contrail prevention starting in early 2021, in order to mitigate for the non-CO2 emissions. A team of planners interpret the predicted weather regarding ISSR and other clouds and give instructions to operations to avoid the ISSR by vertical clearances in the order of 2000 feet after 1800 local time and during the night.

The trial is ongoing and initial findings are: The weather was bad and cold in the MUAC area of responsibility with only few and often short lasting ISSR; traffic was very low due to COVID; the counts are therefore very low and do not permit meaningful analysis for the time being. The accuracy of the ISSR prediction and its verification is a major issue. It should be solved e.g., with many aircraft to equip measurement equipment for relative humidity, a to-be-developed contrail detection system, improved ISSR forecast, or improved decision regarding the duration of ISSR and the impact of contrail.

The internal feedback is positive, MUAC operations profited from the low COVID traffic for a smooth introduction to a new operational element. The thresholds of capacity are still to be evaluated with higher traffic rates.

The resonance on the trial is very high. Almost all our airlines show interest, do support and provide help. Many other stakeholders contacted us and offer support. States are interested.

The MUAC trial for contrail prevention is one contributor and component in a much wider picture of mitigating the climate change. It is an important milestone from theory towards praxis and a stepping stone from science towards engineering.
We hope that the results of this trial will contribute to smart decisions for the future of aviation.

Acknowledgements

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Multi-aircraft environmentally-scored weather-resilient optimised 4D-trajectories

Nick van den Dungen[a]*, Kinanthi Sutopo*[a]*, Xavier Prats*[b]*, Vittorio Di Vito*[c]*, Angelo Riccio*[d]

Abstract

Weather phenomena are one of the biggest causes for significant delays and unpredictable disruptions within air traffic management (ATM) network operations. The changing global climate increases the future severity and frequency of these air traffic disturbing weather phenomena. This deteriorates the predictability of 4D trajectory ATM network planning and potentially increases the delays within air traffic operations. Furthermore, aviation itself has a responsibility to mitigate its climate impact to improve the long-term sustainability of the ATM operations and to contribute to the global effort towards the reduction of anthropogenic climate change. The SESAR 2020 exploratory research project CREATE (Grant 890898) aims to find answers on how to improve the weather-resilience of ATM-operations and to reduce its climate impact. A concept of operations (ConOps) has been developed which describes an integrated trajectory optimisation framework to tactically define environ¬mentally-scored optimised 4D trajectories, for a multi-aircraft airspace configuration, using advanced numerical weather prediction models, combined with air traffic control (ATC) driven demand-capacity balancing methods. The framework will be applied to an en-route use-case focusing on the unorganised traffic over the North Atlantic, and a Terminal Manoevring Area (TMA) use-case focusing on the Naples Capodichino airspace. The optimised trajectories aim to evade thunderstorms and contrail formation regions, whilst minimising CO2, non-CO2 and local air quality (LAQ) impacts.

Introduction

Weather phenomena such as low clouds, fog, rain, lighting and thunderstorms may affect the visibility around an airport or safe operability of aircraft which can cause delays or disruptions in flight schedules. The severity and frequency of these weather phenomena may increase due to the changing climate. As the Earth's surface temperature rises, convection activities increase which ultimately results in more extreme weather phenomena and increased concentrations of water vapor at higher altitudes. The intensification of the severity and frequency of hazardous weather phenomena has already been observed and reported in the most recent IPCC report (IPCC 2021). The frequency and intensity of heavy precipitation levels and hot extremes have increased since the 1950s and the IPCC report states that it is likely that anthropogenic climate change is the main driver. As global warming is unavoidable (the question remains to what extent humans can limit the temperature rise), it is highly likely that hazardous weather phenomena will continue to increase in severity and frequency.

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CREATE research on weather impact on ATM and ATM impact on climate

To research the weather-resilience of air traffic and the anthropogenic climate impact, these relations have been analysed on a local/regional and global scale. On the local scale, the impact of aviation on the environment around Naples Capodichino airport was studied. The consortium partners have access to detailed weather and air traffic data for Naples Capodichino airport, and therefore this airport and its environment were selected as areas of interest for this study. To calculate the hourly and yearly averaged non-CO_2 concentrations on the local scale a Lagrangian particle code (SPRAY LPDM) was used and for the regional scale the FARM model was used. Specifically, the NOx, PM10 and SO_2 emissions were calculated for the local scale due to the airport activities, and for the regional scale NO_x, non-methane volatile organic compounds (NMVOC) and PM2.5 concentrations (CREATE, D2.1, 2021). Furthermore, a detailed description of microscale effects was attempted, considering the presence of buildings and obstacles around the Capodichino airport, using realistic weather data and flight paths (MicroSPRAY LPDM) (CREATE, D3.1, 2021). For the analysis on the global scale, it was recognized that calculating the radiative forcing (RF) effects from contrail formation is subject to uncertainties as current knowledge is insufficient to accurately predict and model (persistent) contrail formation. The RF effects of contrail formation however, are probably the largest of the aviation CO_2 and non-CO_2 climate impacts. (EASA, 2021) Thus, in order to reduce the aviation RF, the possibilities to avoid contrail formation by means of No-Fly Zones (NFZ) (with zero or reduced capacity) are explored within CREATE.

Furthermore, hazardous weather phenomena for ATM operations were identified. Lightning or thunderstorms can cause disruptions to flight schedules; aircraft are surprised by sudden wind changes or strong microbursts/downbursts induced by thunderstorms which can result in aircraft-stall, overstressed airframes and eventually structural failure and loss of control. Therefore, thunderstorms are extremely dangerous and must be avoided by aircraft. For Naples Capodichino airport thunderstorms were identified to be a major disruptive weather scenario. In 2019, over 1000 Dangerous Thunderstorm Alerts (DTA's) were issued in Italy out of a total of 7372 throughout Europe.[1] Given the changing climate, the development of thunderstorms will become more irregular which makes it difficult to consider in the flight planning and execution stage. Therefore, CREATE explores options to integrate tactical accurate thunderstorm forecasting to have a more accurate prediction during the flight and optimise the flight plan whilst taking ATC sector constraints into account.

Objectives

One of the work packages within the CREATE project aims to find a potential solution suitable for the ATM operations to improve weather resilience and reduce its environmental impacts. It has been identified that convective areas related to thunderstorms are a severe disturbing phenomenon for ATM operations (CREATE, D2.2, 2021), and that from all non- CO2 emissions contrail cirrus have a significant impact on the climate (EASA, 2021). This led to the generation of the CREATE trajectory optimisation framework, which aims to fulfil the following objectives; 1) Reduce the weather-induced delay caused by severe weather phenomena, such as thunderstorms; 2a) Minimise the environmental impact of candidate optimised trajectories, related to the evasion of contrail formation regions (CFR) for the en-route use-case;

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[1] *https://get.earthnetworks.com/resources/reports/2019-europe-lightning-report*

2b) Minimise the environmental impact of the candidate optimised trajectories, related to the LAQ for the TMA use-case. The CREATE research has two main contributions towards general ATM research; a) perform tactical trajectory replanning given an updated weather forecast resulting from advanced numerical modelling, b) consider a "multi-aircraft" problem in which ATC restrictions and airspace capacity are considered as well.

Concept of operations

The CREATE concept of operations (ConOps), related to the trajectory optimisation framework, addresses the integration of various design elements; a) multiple aircraft considered in the generation of 4D optimised trajectories; b) Numerical Weather Prediction (NWP) and Ensemble Weather Forecasting (EWF) is used for tactical trajectory replanning by predicting weather scenarios a few hours into the future of a given flight; c) implementing an environmental-score assessment for all proposed candidate routes in the system; d) Air traffic control (ATC) driven demand-capacity balancing (DCB) decision-making process to select overall optimum of the proposed trajectories within a use-case.

Figure 1 illustrates a scenario where multiple aircraft are considered in an arbitrary use case. In this scenario it is assumed that during the flight a set of thunderstorm zones propagates which were not considered in the initial flight planning stage. As such, once the considered aircraft are airborne and in the absence of any tactical trajectory optimisation framework, all aircraft eventually would need to be tactically manually guided by the air traffic controllers (ATCO), in coordination with the flight crew, around the thunderstorm zones to maintain safe flight operations. In air spaces with severe thunderstorm activity and high-density traffic, this becomes a tactical manual-intensive task for the ATC side with a high likelihood of severe weather-induced delays for the considered flights. Furthermore, the manual interventions disrupt the initially proposed flight plans, which has a potential snowballing effect on the delays of flights further downstream in the network.

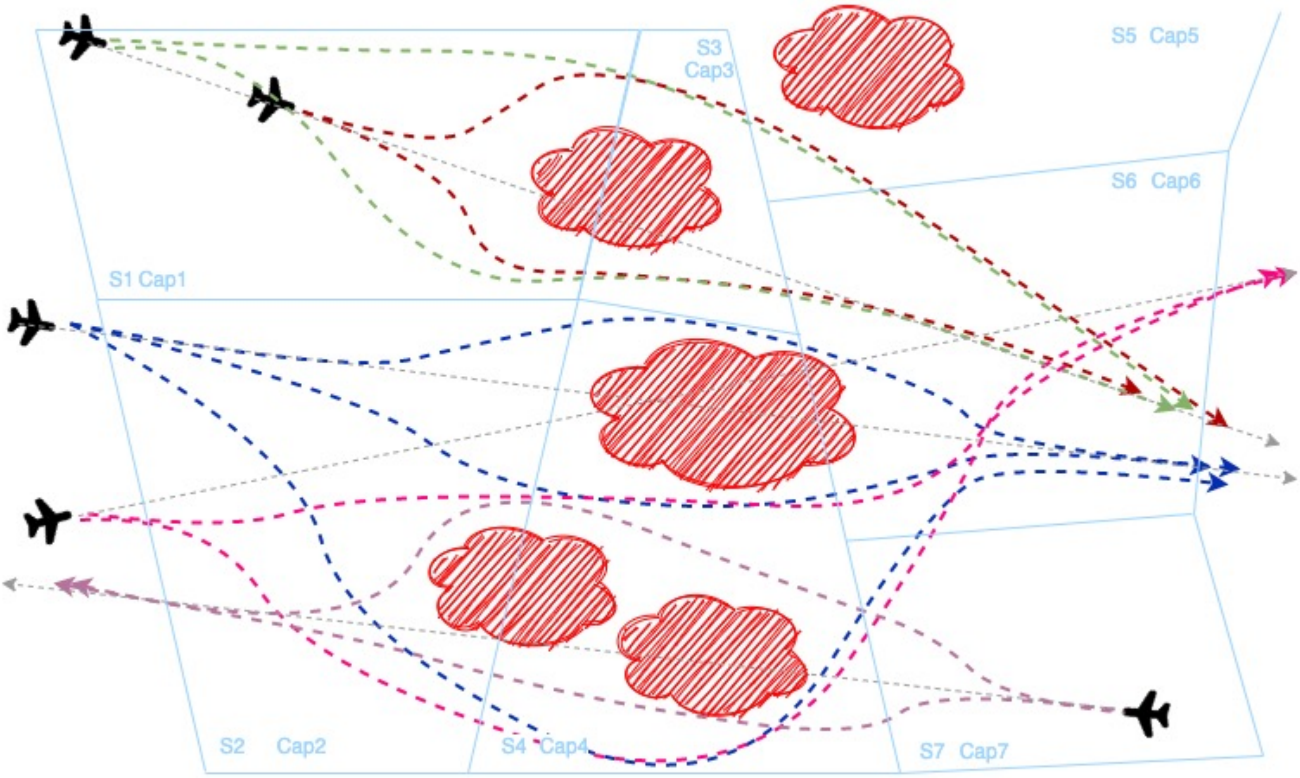

Figure 1: Illustrative example of the CREATE multi-aircraft candidate 4D optimised trajectories

The proposed CREATE ConOps aims to provide a solution to this problem by using NWP and EWF to uplink meteorological forecasts from the ground systems towards the considered airspace users (AU), which can use this data to accurately identify the no-go zones related to thunderstorms at a relatively early stage during the flight. When a thunderstorm front propagates along the flight plan, the AUs can propose candidate optimised 4D trajectories, to evade these areas. Various objective criteria's can be considered to proposes various candidate trajectories per considered aircraft, related to minimum fuel burn, or minimum delay, or minimum environmental impact. The trajectory optimisation framework can be expanded by integrating objective functions which aim to evade climate-sensitive regions related to contrail cirrus formation. Given the fact that contrail formation has a limited vertical domain (Schumann 1996), the trajectory optimisation framework can consider flight level changes to efficiently evade these climate sensitive regions, without any lateral deviation.

Figure 2 illustrates how a centralized DCB component governed by ATC finally determines a global optimum from the set of proposed candidate trajectories by all AUs, to maintain balanced throughput across all airspace sectors considered in the system. This process includes as well an objective to select a solution with an overall minimum environmental impact, related to minimum CO2 and NOx emissions and/or minimum LAQ impact.

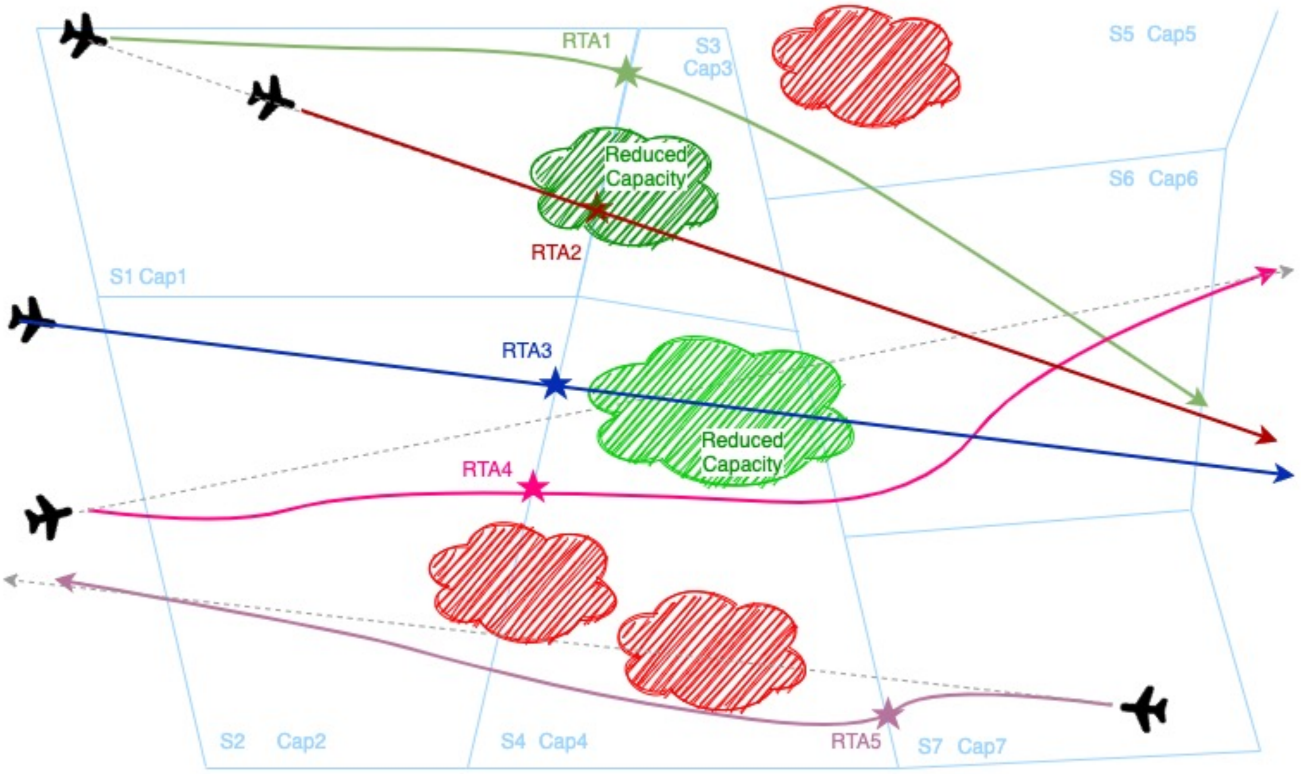

Figure 2: Illustration of the global optimum solution, related to the DCB element of the CREATE framework

Framework methodology

The framework which follows from the design elements consist of the following modules is visualised in Figure 3; a) Meteorological data provider (MDP). This is done via EWP; b) Thunderstorm and contrail-zone predictor (TCP). This is a set of algorithms which translates the EWP data into geographical areas and volumes to be evaded, i.e. the NFZ; c) flight plans (FP), these are the reference plans based on realistic reference flight; d) Sector definitions, these describe the geometric airspace sector layout horizontally and vertically; e) Trajectory Optimisation (TO) with aircraft filtering process (AFP), this module calculates various candidate optimised trajectory per aircraft. The AFP is used to filter per aircraft the relevant applicable data required for the optimisation process. The resulting output of the TO module is a set of new candidate flight plans, for all the aircraft considered in the optimisation problem; f). Trajectory Performance Reconstruction (TPR) with Trajectory Sector List (TSL) and Aircraft performance model (APM) based on BADA 4, this module converts all new flight plans into 4D trajectory profiles with detailed thrust and fuel-burn performances; g) Trajectory Emissions Calculator (TEC) with engine emission tables, this module calculates CO2 and non-CO2 related emissions such as NOx and PM10 based on the output of the TPR module; h) Environmental scores method (ESM), this module calculates per candidate trajectory per flight an environmental impact score. For the en-route this will be related to the CO2 and NOx forming and for the TMA use-case this will be related to LAQ; i) Tactical Weather avoidance and demand and capacity balancing (TWADCB) based on available sectors capacity (SC); this module contains a set of algorithms which determines the global optimum of the computational scenario based on balancing the ATC load across all sectors, by selecting the best candidate flight plans out of all proposed options of the multiple considered aircraft; j) Decision making and pareto front analysis (DMPA), this module contains an ATC-based evaluation of the overall recommend solution scenario with the selected candidate routes. A human will be presented with the solution scenario and does a final sanity check on selected candidate trajectories.

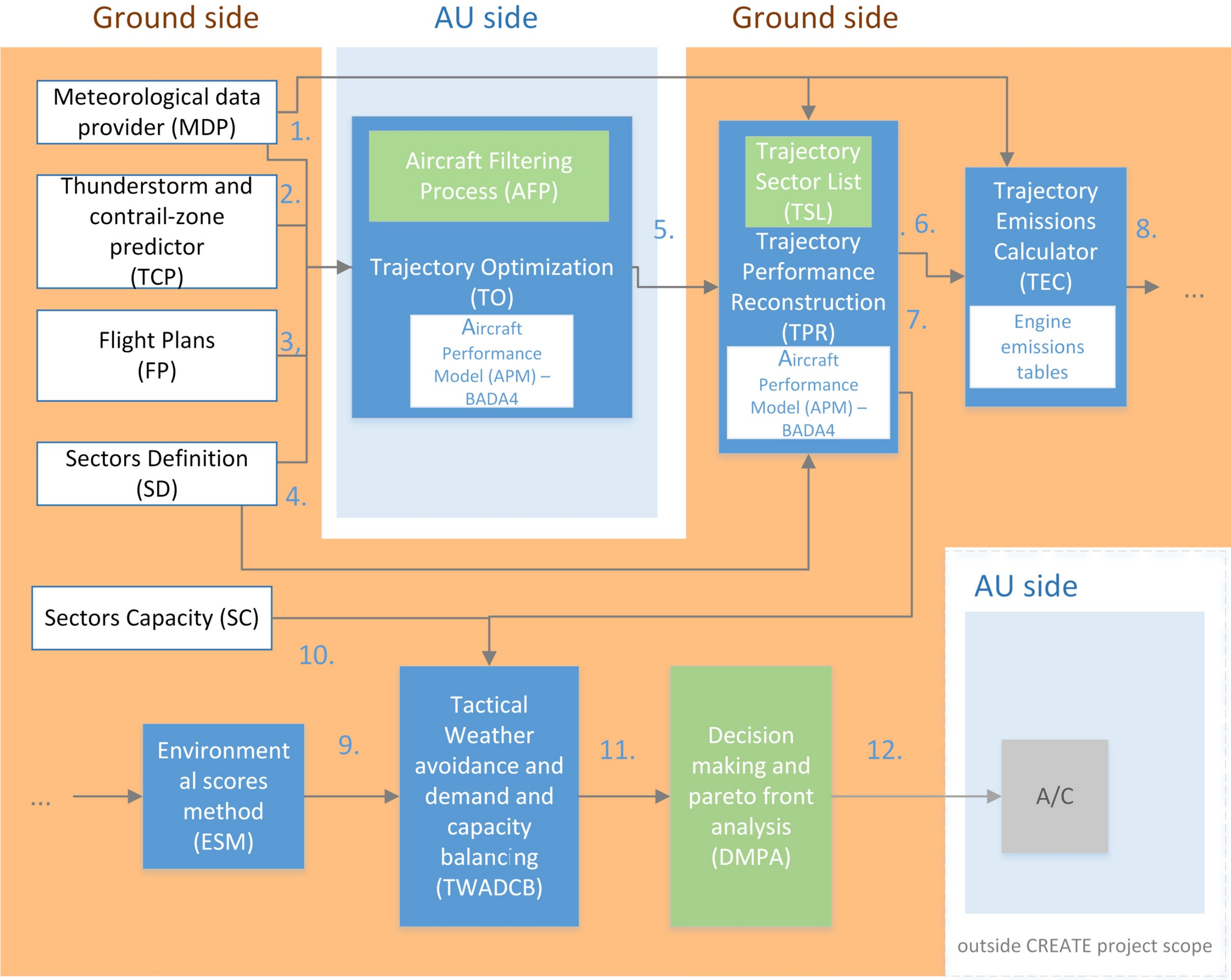

Figure 3: Overview of the CREATE framework related to the concept of operations

Ensemble weather forecast method

One of the key elements in the CREATE framework is the implementation of advanced weather modelling tools via NWP and EWF (ensemble NWP system). This allows flights to acquire accurate weather predictions during flight, which supports the tactical route optimisation process for long flights. The method used within the CREATE framework relies on taking the average EWF once a new weather ensemble is created every “x” min. The EWF members are used to calculate probabilistic NFZ within the TCP module, such that the weather prediction elements within the CREATE framework are not purely deterministic, but still include a probabilistic element. In previous SESAR research a method has been developed to provide the ATC DCB unit an optimised trajectory per EWF member. (IMET, 2015)

However, since the CREATE framework considers multiple aircraft each providing multiple candidate trajectories, it has been decided to apply a simpler method to reduce the complexity at this exploratory phase of the research programme. This strategy supports the design philosophy to focus on providing an integrated framework to select a global optimum from the proposed candidate trajectories of the multiple aircraft considered in the use-cases.

Thunderstorm predictor via EWF

The TO module of the CREATE framework is triggered by the identification of thunderstorm related NFZ which require the original flight plan to be updated. Thunderstorms can be identified by the presence of high Convective Available Potential Energy (CAPE) values, which is derived from the ensemble NWP system. CAPE describes the amount of work that the upward buoyancy force would perform on a given air parcel if it travels upward through the atmosphere. (ECMWF, 2019) A positive CAPE indicates that the air parcel has the potential energy to rise and thus it indicates atmospheric instability. The higher the CAPE value, the more instable the atmosphere and the higher the possibility of thunderstorms and hail. A thunderstorm is defined if the most unstable CAPE (MU-CAPE) is larger than a critical threshold value for which severe thunderstorm form. The MU-CAPE method loses the vertical distribution of thunderstorms due to the integral along the vertical direction. As such, the TO module is limited to always evading thunderstorms laterally.

Contrail-zone predictor via EWF

The TO module of the CREATE framework is triggered as well by the identification of contrail cirrus related regions which require the original flight plan to be updated. Contrail-sensitive areas can be selected using the Schmidt-Appleman Criterion (SAC) (Schumann, 1996). Given the thermodynamic atmospheric conditions (temperature, air pressure and relative humidity) from the ensemble NWP system, and aircraft-specific parameters (fuel emission index, specific combustion heat and aircraft propulsive index), the SAC theory predicts conditions at which contrails can form, and whether these contrails will persist. According to the SAC, the temperature at which contrails form at the actual relative humidity is calculated for each vertical level. In this manner, the minimum and maximum height at which contrails are persistent is calculated for each model grid column. Therefore, the TO module could also use flight level changes to fly over or under a given contrail NFZ. Since the local atmosphere can be unstable, contrail formation conditions can change on the short term. It should therefore be noted that the contrail-zone predictor requires regular updates to account for the instability of the atmosphere.

Trajectory optimisation criteria and objective functions

The following considerations are used to provide the candidate optimised trajectories: a) the alternative trajectories will avoid the conflicting NFZ (one or more); b) the alternative trajectories will minimize the deviation from the original path; c) the alternative trajectories will be calculated in the 2D framework and after that the vertical profile will be associated to them; d) the alternative trajectories will have minimum curvature radius in the 2D framework that will comply with the nominal performances of the considered aircraft;

e) the alternative trajectories will have vertical flight path angle envelope that will comply with the nominal performances of the considered aircraft.

Environmental scores method for en-route

The ESM for en-route takes both CO_2 and non-CO_2 effects into account. Most important to identify is that the climate impact of CO_2 is directly related to emission amount and independent of time and place of emission, whereas the climate effect of non-CO_2 emissions is highly dependent on time and location of emission, due to the complex interaction with background concentration and influence of atmospheric and engine characteristics. The impact of contrails can be linked to the likelihood of flying through contrail formation zones, and the impact of NO_x¬ emissions is dependent on NO_x background concentrations and engine characteristics. A trajectory with reduced CO_2 emissions can result in increased non-CO_2 climate impacts, e.g. because it will likely fly through CFRs or because lower CO_2 emissions are due to increased engine efficiency which leads to increased NOx emissions. Furthermore, the time horizon of the impacts of CO_2 and non-CO_2 impacts vary, which is taken into account as well. The ESM for en-route takes all these variables into account and weighs these impacts into a final environmental score.

Environmental scores method for TMA

The ESM for the TMA starts with dividing each aircraft trajectory into segments, each one with the related portion of the emissions. The fate of those emissions in the atmosphere is then followed along multiple Lagrangian „environmental trajectories“, calculated on the basis of current 3D meteorology and turbulence fields. The spread of each trajectory set gives an indication of the diffusion potential of the atmosphere at that time and location, and the environmental score of the aircraft trajectory is calculated as the sum of the spreads associated to all segments. This then can be related to local air quality.

Candidate routes selection via DCB

Within the TWADCM module an algorithm will perform the selection of the most suitable candidate flight plan for each and every aircraft by considering a weighted mean of the associated scores to each candidate trajectory based on both the environmental score associated to the trajectory and the sector capacity resulting from the associated path execution. For each alternative trajectory selected for the aircrafts of interest, the TWACB module also calculates the associated expected delay with respect to the nominal one.

Discussion on framework operational application

In the first phase of the project it has been established that the CREATE framework should be developed and applied to two different use cases, i.e. en-route and TMA. The weather, climate, and ATC specific phenomena have different characteristics per use case, yet equally important. Since the CREATE framework can be developed in a generic manner to be applied to both use cases, it is investigated what the framework specificities and potential benefits are per use-case.

En-route

For the en-route use case an area of interest needs to be defined which is sufficiently interesting to research based on the presence of CRFs and thunderstorm fronts. For European flights, the trans-Atlantic long-haul flights is an interesting use-case to consider. Since thunderstorms are likely to propagate over central mainland US[2] and Mediterranean Europe[3], it is likely that these phenomena affect the initial and last parts of the en-route flight segment. As researched by Irvine et al. (2012), the North Atlantic Ocean shows strong contrail formation. Therefore, it is likely that the middle part of the en-route flight segment for a trans-Atlantic flight is affected by contrail formation. Another reason why the North Atlantic routes are interesting to research is that different segments of the flight will be triggered by either thunderstorm propagation or contrail formation, due to the atmospheric conditions in which both phenomena persist. In terms of the ESM, the Lagrangian method related to LAQ cannot be applied because it considers assumptions which are only valid for low altitudes and is mainly relevant for populated areas.

TMA

Within CREATE Italy will be considered as a particular country of interest, given its many thunderstorm activities throughout the year. Furthermore, the availability of detailed local meteorological and environmental information for Naples Capodichino airport led to the selection of the Naples TMA as use-case for the TMA operations. The CREATE research shall investigate how the TMA operations, including continuous descent operations (CDO), will be affected due to the application of the CREATE framework. Given the meteorological conditions which are required for contrail cirrus to propagate, i.e. cold/stable/moist atmospheres, it is unlikely that contrail cirrus will affect the TMA use-case.

Conclusion

The work presented shows the CREATE ConOps, which is a framework considering multi-aircraft environmentally-scored weather-resilient optimised 4D trajectories, aiming to evade thunderstorm areas and contrail forming regions, with the objective make the ATM operations more weather-resilient whilst minimising its environmental impact. By using EWF various candidate optimised trajectories can be developed where a centralised ATC-based DCB decision-making process will select the global optimum for a given use-case scenario.

The next step in the CREATE research is to demonstrate the effectiveness of the framework on the en-route and TMA use-cases, which are the North Atlantic and Naples TMA respectively. Per use-case, validation simulations will be performed to derive conclusions whether the CREATE framework can effectively reduce the ATM delays and environmental impact, compared to applicable reference scenario(s).

Acknowledgements

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[2] *https://www.spc.noaa.gov/wcm/*

[3] *https://www.essl.org/cms/a-climatology-of-thunderstorms-across-europe/*

Impacts" (SESARH2020-ER4 CREATE) within the European Union's Horizon 2020 research and innovation programme under grant agreement No 890898. The CREATE consortium is formed by ATM/ Meteo/Environmental specialists from the Royal Netherlands Aerospace Centre (NLR), Universitat Politècnica de Catalunya (UPC), Centro Italiano Ricerche Aerospaziali (CIRA), Università degli Studi di Napoli Parthenope (UNIPARTH, project coordinator), ARIANET, Ilmatieteen Laitos (Finnish Meteorological Institute, FMI), and Institute for Sustainable Society and Innovation (ISSNOVA).

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Session 3

Reducing CO_2 emissions – Interdependencies and potential trade-offs

Toward novel environmental impact assessment for ANSPs using machine learning

Gabriel Jarry[a], *Daniel Delahaye*[b]

Abstract

The return of air traffic after the coronavirus crisis requires an increasing involvement of all players in environmental issues. The evaluation, measurement and monitoring of environmental performance is therefore an essential issue for the Air Navigation Services Providers (ANSP).

This paper presents the ACROPOLE project, which explores and develops novel metrics and indicators using machine learning in order to assess the environmental impact (fuel consumption, CO2 emissions) and to analyze the 3D inefficiencies of aircraft operations with an ANSP point of view. The project uses artificial intelligence such as supervised learning models built with airlines that enable an accurate estimation of on-board parameters such as the real time fuel flow from basic radar data.

Historical radar data over France from the French DSNA were used to illustrate the computation of these indicators at Charles de Gaulle airport, and underline potential inefficiencies in terms of airspace structures and best practices. In this paper, the metrics and the methodology will be introduced, discussed and illustrated.

Introduction

The return of air traffic after the coronavirus crisis requires an increasing involvement of all players in environmental issues. The evaluation, measurement and monitoring of environmental performance is therefore an essential issue for the Air Navigation Services Providers (ANSP). Several agencies and programs, such as SESAR in Europe and NextGen in the United States, had already taken ambitious environmental targets before the crisis. For example, SESAR 2020 wants to contribute to a 10% reduction in CO2 emissions [1], which implies to significantly reduce the burned fuel per flight by 2035.

From an ANSP point of view, carrying out environmental monitoring implies, on the one hand, being able to accurately measure the various underlying parameters (fuel consumption, pollutant emissions, noise emissions), and on the other hand, developing and deploying at large scale relevant indicators in order to monitor and identify potential system inefficiencies.

This paper presents the ACROPOLE (AiCRaft OPerations nOise and fueL Efficiency) project, which explores and develops novel metrics and indicators using machine learning in order to assess the environmental impact (fuel consumption, CO2 emissions) and to analyze the 3D inefficiencies of aircraft operations with an ANSP point of view.

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The paper will be divided into four parts. Firstly, a state of the art on flight efficiency metrics and parameter estimation will be presented. Secondly, the extension for door-to-door operation of a previous research [2] on neural network based on-board parameter estimation will be presented. Third, a set of metrics and indicators will be presented based on these models to quantify the global and ANSP efficiencies. Finally, a use case will be developed to illustrate the use of these indicators in the approach phases.

State of the Art

Flight efficiency evaluation

Identifying the causes of air traffic inefficiency has been an important topic in ATM research for decades. Various causes of inefficiencies such as airspace structure, congested areas or adverse weather were discusses by Reynolds [3], [4]. He also presented metrics of different kind (lateral, vertical, speed of fuel based metrics) to analyse and monitor flight inefficiencies.

These metrics are usually based on a reference trajectory against which a flight is compared. Hence, the definition of this reference trajectory is crucial.

Both in Europe and in the United States (US), current indicators [5] compare the trip distance of planned or actual trajectories with great circle distance (orthodromic trajectories). This only enables a lateral inefficiency measurement without taking into account the vertical inefficiency, and furthermore it is not always reflecting a fuel optimal trajectory. Additional, metrics were developed in order to tackle this problem, in particular Eurocontrol [6] proposed to evaluate en-route vertical efficiency using the maximum altitude observed in the flight plan. This also induces potential bias if other cruise segments are flown at lower altitude.

Another metric, called 3Di metric [7] was developed by the United Kingdom (UK) ANSP to measure flight efficiency. It compares the fuel burn of each flight to its corresponding optimal reference trajectory per aircraft type, requested flight level and flown distance. However, the choice of fuel reference values could induce bias since it might not be optimal [8].

More recently, Prats et al. have proposed [9] a set of new performance indicators that aim to capture the environmental impact of aircraft operations, in terms of distance and fuel inefficiencies. They produce different optimal trajectories, which enable the identifications of inefficiencies at different level. They also suggest that machine learning could help enhancing those kinds of indicators by providing more accurate estimation of parameters such as fuel flow.

Research has also been conducted by Pasutto et al. on the development of vertical flight efficiency indicators for the descent [10] and cruise phases [11]. This research highlights the use of an indicator which is defined as the surface between a given altitude profile and one of the reference profile, expressed in feet hour. The two references are the best and the ideal performers. These references are very useful and accurate in identifying airspace and operational inefficiencies and good candidate of use. This metric is a fuel proxy, and is easily reproducible.

Within this context, this paper will investigate the use of machine learning models for the development of large scale environmental indicators.

Parameter estimation

Estimation, sometimes called regression, is a well known mathematical problem. It is divided into two main approaches: the physical model-driven estimation, which had been for a long time the most popular estimation process, and the data-driven regression, which has been more and more used during the last decade with the rise of machine learning and deep learning, showing equal or even more precise predictions.

Physical model-driven parameter estimation consists in using physical equations and models to estimate target features. Usually, differential equation problems are solved or assumptions are taken to give simplified estimations. In aviation, these models have been studied for a long time in different areas such as aerodynamic [12], or fuel-efficiency [13]. These models may need important computational resources.

On the other hand, data-driven models try to estimate the underlying physical models using available data. The learning phase can be costly in computational resource, however, the prediction phase is then instantaneous, which presents interesting properties in real-time operations. Different works were led to compare physical models, such as the Eurocontrol aircraft performance model: BADA [14], to data-driven models [15]. Clemons et al. identified first order enhancements to airport surface fuel burn modeling [16]. Turgut et al. used BADA model to estimate aircraft fuel flow for a three-degree flight-path-angle descent [17]. Chatter et al. used BADA model to give a fuel burn estimation [18].

Many studies have been conducted to predict on-board parameters using ground-based surveillance systems. Delahaye et al. proposed estimations of the True Air Speed and the wind using radar data [19], [20]. Sun et al. estimate the aircraft mass using Bayesian inference methods [21]. Chati et al. proposed different learning model types such as Gaussian Process regression [22] and tree-based classification [23] to predict the aircraft fuel flow rate. The proposed prediction models outperform the classical physical BADA models.

Other algorithms such as neural networks have also been investigated to estimate the fuel flow rate but with access to many on-board parameters [24]. Peyada et al. presented a new filtering technique based upon a neural network and Gauss-Newton method to estimate aircraft parameters [25], [26]. A recent type of neural network called Long-Short Term Memory has proven to be very efficient on time series data to predict trajectories [27] or hard landings [28].

Previous research [2] was lead to use feed forward and LSTM neural networks to predict onboard parameters such as fuel flow, flaps and gear configuration during the approach phase, showing very low error with only simple parameters such as ground speed, altitude and vertical speed. This paper will extend those models from gate-to-gate and study their use in ATM performance indicators.

Machine learning models and performance

This section describes the neural network architecture and performance obtained within the new framework. In the previous research [2] the neural networks were trained to predict onboard parameters during approach and landing phases. In this paper, their extension to all flight phases will be presented.

Data pre-processing and network architecture

The models are trained using as input the last 15 points of radar equivalent parameters (altitude, ground speed, vertical speed, and true air speed) from Flight Data Records of different airlines. The available data set are composed of different aircraft types such as A319-111, A320-214, B737-8K2, A330-223. The result will be illustrated on the A320 data set which is composed of around 16 500 flights. The data-set is split into three subsets for training (14 000 flights), test (1425 flights) and validation (1000 flights).

Two input configurations for the neural network were tested: with or without the true air speed. The prediction parameter mainly considered is the fuel flow which will feed the performance indicators but other parameters such as the aerodynamic configurations (flaps and gear settings or speed brakes use) could be learned similarly.

Regarding the network, a feed-forward architecture was selected. It consists of a batchnormalization input layer, followed by three dense layers with 50 neurons and ReLu activation functions, finally the output layer is a dense layer with 1 neuron and a ReLu activation.

The learning phase was processed using the Adam optimizer [29] with decay and the loss function used is the least square error. The learning rate is $10{-}3$ and the decay is $10{-}9$. Each model is trained during 2000 epochs, and the best network over the test set is kept. The performance is then computed over the validation set.

Model performance

The indicators are computed over 1000 flights (an equivalent of around 8 000 000 positions) for the two configurations (with or without the true air speed), for each phase of flight, and for the fuel flow (in kg/h) and the aggregated consumption (kg) over the phase. The performance indicators for the two models are detailed in Table 1 and Table 2.

In order to compare the performance of the different models, four different indicators were used: the Mean Error (ME), the Mean Absolute Error (MAE), the Mean Absolute Percentage Error (MAPE), and the Pearson correlation score (r). Let $\mathcal{D}$ be a set of couples input-output (x, y), and h a model to evaluate, the three first indicators are computed as

$$ME(h,\mathcal{D}) = \frac{1}{|\mathcal{D}|}\sum_{(x,y)\epsilon\mathcal{D}} h(x) - y \qquad (1)$$

$$MAE(h,\mathcal{D}) = \frac{1}{|\mathcal{D}|}\sum_{(x,y)\in\mathcal{D}} |h(x) - y\,| \qquad (2)$$

$$MAPE(h,\mathcal{D}) = \frac{1}{|\mathcal{D}|}\sum_{(x,y)\in\mathcal{D}} \frac{|h(x) - y|}{y} \qquad (3)$$

Phase	MAPE$_{fuel}$ (%)	MAE$_{fuel}$ (kg/h)	r_{fuel}	Samples #	MAPE$_{conso}$ (%)	MAE$_{conso}$ (kg)	ME$_{conso}$ (kg)	Flight #
ALL	6.96	59.2	98.9	7988512	2.19	113.6	-11.9	1000
TAXI	11.72	47.1	23.4	369704	4.97	3.5	-0.1	1000
CLIMB	2.06	46.7	99.1	1347940	1.41	24.0	2.5	1000
CRUISE	4.33	52.0	81.4	4111650	3.45	87.6	-9.0	995
DESCENT	14.24	72.1	94.5	1276614	4.94	19.9	-3.0	999
APPROACH	18.41	125.3	84.7	224834	7.51	7.0	0.3	998

Table 1: Predictive performance of the model without true air speed on 1000 A320 validation flights. The prediction error for the fuel flow and consumption are displayed over flight phases using mean absolute percentage error (MAPE), mean absolute error (MAE), Pearson correlation score (PC), and mean error (ME).

Phase	MAPE$_{fuel}$ (%)	MAE$_{fuel}$ (kg/h)	r_{fuel}	Samples #	MAPE$_{conso}$ (%)	MAE$_{conso}$ (kg)	ME$_{conso}$ (kg)	Flight #
ALL	5.95	50.5	99.1	7988512	1.73	92.0	1.5	1000
TAXI	11.21	45.5	23.4	369704	4.92	3.4	0.4	1000
CLIMB	1.66	38.2	99.2	1347940	1.19	20.3	4.0	1000
CRUISE	3.68	44.1	86.7	4111650	2.8	72.5	-2.8	995
DESCENT	11.17	56.2	96.2	1276614	2.88	10.4	2.0	999
APPROACH	16.9	115.0	86.7	224834	6.51	6.1	0.3	998

Table 2: Predictive performance of the model with true air speed on 1000 A320 validation flights. The prediction error for the fuel flow and consumption are displayed over flight phases using mean absolute percentage error (MAPE), mean absolute error (MAE), Pearson correlation score (r), and mean error (ME).

For these indicators, the smaller its value is, the more accurate the prediction is. Finally, the Pearson correlation score indicates how well the curve of the predicted parameter follows the actual curve. The closer the score is to 1, the better the prediction is. It is computed using the following equation:

$$r(h,\mathcal{D}) = \frac{\sum_{(x,y)\epsilon\mathcal{D}}\left(h(x) - \bar{h}\right)(y - \bar{y})}{\sqrt{\sum_{(x,y)\epsilon\mathcal{D}}\left(h(x) - \bar{h}\right)^2}\sqrt{\sum_{(x,y)\epsilon\mathcal{D}}(y - \bar{y})^2}} \qquad (4)$$

where h (resp. $\bar{y}$) is the average of h(x) (resp. y) over $\mathcal{D}$.

First of all, we observe that as expected the model with the true air speed obtains a better performance: when the MAPE and MAE for the fuel flow are of 6.96% or 59.2kg/h for all phases without the true air speed, it decreases to 5.95% and 50.5kg/h with it. We observe similar characteristics for the aggregated consumption: 2.19% and 111.6kg error per flight vs 1.73% and 92kg per flight in average. Additional information is given by the Person correlation score, which is really high 98.9 (resp. 99.1), and the ME -11.9kg (resp. 1.5kg) which implied an almost 0-centered error distribution. It underlines that the prediction is really following the overall shape of the curve and is able to capture variation pretty well. Besides, a consumption study over several flights would induce a very small error in the total consumption. We were not able to apply BADA 4 fuel flow estimation, however and as a comparison, the BADA database indicates that for the aircraft type A320-214 the estimation error is in average of 67.8kg/h (1.13kg/s), and was evaluated over less samples (101 370 points). As a remark, it appears that even without the true air speed, the model shows a good performance.

More detail among flight phases will be now discussed with a focus on the true air speed model since the behaviors are similar for both of them. As in the literature [22], the models present different performances among flight phases. They perform well during climb, cruise and descent. We observe lower performance for approach but with still a high correlation which indicates that the model is able to capture variations.

Finally, the lower scores are observed for taxiing and parking. Nevertheless since these phases only account for a short part of the gate to gate flight and are not always studied, it does not have an important impact on the global model performance in terms of consumption estimation. Enhancement for these flight phases could be done if they need to be studied independently.

Scaling fuel flow using proxy aircraft

In previous research [2], we have shown that these models present scaling capabilities. In other words a model trained on a particular aircraft type, could also be used to predict the fuel flow from another aircraft type. In this subsection we will describe the methodology we propose to scale aircraft using proxy aircraft type and illustrate its use to predict B737-8K2 fuel flow from A320-214 model presented in last section.

In general situation we will consider using aircraft as a proxy for fuel when it has similar flight characteristics. In our case, we try to group together A320 and B737. Since we trained an A320 model, the objective was to evaluate its use to predict on B737 flights. The process consists in building a scaling function using the ICAO aircraft engine emissions databank [30]. Fuel flow coefficients at different characteristic thrust power (take-off, climb-out, approach, idle) are given for each engine type. The ratio of these coefficients between two aircraft types can be used to scale the fuel flow in each flight phases. The coefficients for A320-214 and B737-8K2 are given in Table 3. The ratio of the idle coefficients is used for taxi, the ratio of climb coefficients is used for climb phases, approach coefficient ratio for approach phases. Finally, we fixed empirically the last coefficients: 0.9 climb coefficient ratio for cruise and 0.85 climb coefficient ratio for descent.

Aircraft	Idle	Approach	Climb-out	Take off
A320-214	374.4 kg/h	1123.2 kg/h	3366.0 kg/h	4075.2 kg/h
B737-8k2	417.6 kg/h	1256.4 kg/h	3754.8 kg/h	4622.4 kg/h

Table 3: Fuel flow coefficients from ICAO engine emissions databank for A320-214 and A319-111. These coefficients are used to create scaling coefficient for the fuel flow estimator

The following process was applied to a data set of 1000 B737 flights in order to evaluate the performance of the process. First, the A320 model with true air speed was applied on B737 parameters to predict the fuel flow. Second, the fuel flow was scaled using the scaling ratio coefficients presented previously. Finally, the performance of the scaling is measured using the same metrics as in the previous section and summarized in Table 4. Overall, we observe a short decrease in the model performance in terms of Mean Absolute Percentage Error (2.72% in the aggregated consumption instead of 1.73%) but still a high correlation of fuel flow estimation during all phases except taxiing. This high correlation indicated that the model is still able to capture the variations in the fuel flow estimations. The high correlation also underlines that the fuel estimated by one model is a good candidate metric to identify fuel inefficiencies. Indeed it enables to identify extra-consumption without assumption on the aircraft type. We observe that the mean error (ME) is not 0-centered, so it implies that the scaling induced short deviations.

Phase	$MAPE_{fuel}$ (%)	MAE_{fuel} (kg/h)	r_{fuel}	Samples #	$MAPE_{conso}$ (%)	MAE_{conso} (kg)	ME_{conso} (kg)	Flight #
ALL	9.59	82.9	96.0	9286056	2.71	153.7	-52.5	1000
TAXI	22.73	85.4	25.0	365444	8.78	6.8	-6.0	1000
CLIMB	4.26	103.0	97.1	1161423	2.49	38.0	-18.3	1000
CRUISE	4.5	51.1	79.4	5302375	3.3	102.6	-32.0	998
DESCENT	15.42	68.8	94.2	1505903	4.01	15.5	-0.7	999
APPROACH	17.66	143.8	83.5	199789	7.96	7.7	2.0	1000

Table 4: Predictive performance of the model with true air speed on 1000 B737 validation flights with scaling coefficients. The prediction error for the fuel flow and consumption are displayed over flight phases using mean absolute percentage error (MAPE), mean absolute error (MAE), Pearson correlation score (r), and mean error (ME).

This observed deviations could be mitigated by an optimization process to define the scaling coefficient on each phase with an access to a few FDR samples as proposed in [2]. However, the objective here was to evaluate the use of a methodology that is only based on available data such as ICAO engine emission databank. Further considerations will be made in the discussion section.

Indicators

Aircraft operations, flight phases and flows

In the context of proposing environmental performance indicators for ASNPs, where the main focus is on commercial aviation, four types of operations are distinguished:

- International departures: aircraft taking off from a local airport and leaving the airspace;
- International arrivals: aircraft that enter the airspace and land at a local airport;
- Domestic flights: aircraft that take off and land at a local airport;
- Fly over operations: aircraft that enter and leave the airspace.

For each type of operation, it is relevant to identify the overall environmental impact (from the first to the last radar plot) or to have a refined view to meet local needs by focusing on particular phases of flight (departure, en-route, arrival). These phases are generally determined by concentric circles around the airport hubs (50NM, 100NM or 200NM), or as required by cutting the flights at the tops of climb (TOC) and tops of descent (TOD), or at geographical airspace boundaries.

There is a need for indicators at two levels. On the one hand, at national level, to enable the evolution of ANSP performance to be monitored. These indicators must allow:

- To evaluate and monitor the quality of services provided by the ANSP independently of the fleet operated in the airspace. These indicators must take into account the constraints inherent in the structure of the airspace and be capable of adapting to its potential evolution.
- To quantify the fuel or CO2 balance associated with this quality of service, taking into account the typology of the fleet.
- To evaluate and monitor the structural environmental balance of air operations independently of the fleet operated in the airspace and thus enable the impact of potential changes in its structure to be measured.
- To quantify the fuel or CO2 balance associated with this structural balance by taking into account the typology of the fleet.

On the other hand, at the local level, to enable the control centres to meet their own performance analysis needs.

Flow identifications and definition of a reference or a best performer

Performance indicators are usually computed as the difference and/or ratio between the actual flight and an ideal. The ideal is, for example, the direct orthodromic flight between the first and the last point. However, this ideal is usually not achievable and the indicator therefore does not take into account operational airspace constraints or departure and arrival procedures. In addition, trajectory flows can be quite different in terms of distance flown and are therefore difficult to compare.

A first solution could consist in clustering trajectories by flows. Flows are determined by clustering trajectories in pairs (airspace entry point or departure airport QFU; airspace exit point or arrival airport QFU). By integrating the notion of flows, the results in terms of consumption are then directly comparable between trajectories of the same flow. Aggregation on a larger scale can only be used to draw up a global consumption balance sheet, but not to compare flows between them. The problem with this approach is that there is no reference to determine whether the consumption observed is efficient or not.

An additional step is the introduction of a reference, for example the notion of a best performer. The best performer is a reference within the flow, selected for its efficiency with regard to a given criterion. Unlike an ideal performer, which would be the optimal trajectory without constraints, the best performer takes into account the constraints associated with the flow, and it is also a flight that is achievable since it corresponds to an existing trajectory. In the case of fuel consumption, a best performer is a flight path that has one of the best observed fuel consumption. One way to determine this is to obtain the distribution of the fuel consumption of the flights in this flow broken down into quantiles. Then, select the first flight whose consumption is below a quantile value (e.g. quantile 2%). An important point about best performers is that they may change over time (e.g. when a procedure or airspace changes etc.). Such changes should not theoretically lead to any variation in the indicator, and there should be a possible update of the best performer at a certain date to allow the new best performer to take into account changes due to the modification of the structure.

Thus, the consumption of the best performer can be subtracted from the consumption of the flights to obtain a difference in consumption compared to the best performer. The advantage here is that the notion of absolute consumption is retained. This difference also allows a first level of aggregation for flows with similar definitions. In particular, for departures or arrivals defined with identical assumptions (e.g. in a 50NM or 100NM circle). Deviations can then be compared from one hub to another or for en-route flows of comparable distance. The differences in consumption can also be summed up to get an overall balance.

Nevertheless, the en-route part raises a final question about the comparability of flows with very different flight distances. It is no longer possible to keep the absolute consumption and a relative comparison must be considered. By taking the difference in consumption between a flight and the reference such as the best performer, then dividing it by the consumption of this reference, we obtain a percentage difference in efficiency compared to this reference. However, the notion of absolute comparison is lost; a difference in the indicator will no longer be quantifiable directly in terms of kg of fuel consumed but in % of additional consumption compared to the reference or the best performer of the flow considered.

Below is a summary of the three categories of indicators. Let us assume a metric M (for example total consumption), on a given flight f and a reference r on the same flow. We have the absolute indicator, which is comparable within the flow and which can be summed up to obtain global consumption balances:

$$M_f \qquad (5)$$

The absolute deviation in relation to a reference (for example a best performer), the average of which is comparable between flows of the same nature, which can also be summed up to obtain a global deviation balance on the flow:

$$M_f - M_r \qquad (6)$$

The relative deviation with respect to a reference or a best performer, whose average is comparable whatever the flow is given by:

$$\frac{M_f - M_r}{M_r} \qquad (7)$$

ANSP performance vs global performance

As detailed above, there is a need for an assessment of the French ANSP performance that would be independent of aircraft type to allow for an accurate assessment of the quality of services provided and the impact of the structure without bias associated with the fleet operated.

A first step in proposing indicators could be to group operations by broad categories of aircraft with similar flight envelopes (jets, turboprops) or wake turbulence catagories (L, M, H). Then, within these categories, it would be necessary to normalise the consumption obtained in order to make it independent of the aircraft type.

However, machine learning models have important generalisation properties. As presented in the previous section, a fuel flow estimation model trained on an A320, gives an estimate of fuel consumption on a trajectory of another aircraft type such as an B737, which is highly correlated to the actual fuel consumption of the aircraft. In other words, the model is capable of highlighting the phases where consumption increases and decreases despite being trained on another aircraft type. It is therefore possible to imagine an indicator that uses the same consumption estimation model for a set of aircraft types with similar flight envelopes and thus allows a comparison with an intrinsically normalised consumption. This is equivalent to estimating consumption by considering that all trajectories are flown by the reference aircraft for this group of aircraft.

Regarding the global performance, we are interested in evaluating the real consumption and pollution emitted within the ANSP airspace, which depends on each aircraft type and is therefore dependent on the fleet operated.

Indicators proposal

This section presents a proposal for national and local indicators for the evaluation of environmental performance associated with fuel consumption and therefore pollutant emissions.

a) KPI 1: *ANSP Fuel best practice relative deviation*: the first indicator aims to measure the quality of the services provided by the ANSP without taking into account the fleet operated.

Each trajectory is studied by flow, the consumption associated with the trajectory is computed for the reference aircraft type corresponding to the associated aircraft group. It is then compared in a relative way to the consumption of the best performer predetermined for the flow. The score obtained corresponds to a percentage difference in consumption (computed from the reference model), compared to the best performer for the flow associated with the trajectory.

Suppose that Cref is the fuel consumption computed from the reference model, f is the flight studied and BP is the best performer of the flow associated with f we have:

$$KPI_1(f) = \frac{C_{ref}(f) - C_{ref}(BP)}{C_{ref}(BP)} (+0.1) \qquad (8)$$

NB: we can add an offset to the score of +0.1 to avoid negative deviations. The best performer will have a score of 0.1. A score of 0 is then equivalent to a consumption 10% lower than the best performer of the associated flow.

The national indicator is the aggregation of this score as an average and standard deviation for a given time period and for all trajectories in the French airspace.

b) KPI 2: *Real fuel best practice absolute deviation*: the second indicator aims to measure the equivalent of this ANSP deviation in terms of the difference in kg or ton of fuel compared to the best performer, taking into account the type of fleet.

Each trajectory is always studied by flows, the actual consumption associated with the trajectory is computed taking into account the aircraft type of the flight. It is then compared in absolute terms to the consumption of the best performer predetermined for the flow, considering that the trajectory of the best performer is flown by the same type of aircraft as the trajectory studied. The score obtained corresponds to a difference in kg of consumption compared to the best performer of the flow associated with the trajectory.

Suppose that C_{model} is the fuel consumption computed from the model corresponding to the aircraft type of the studied trajectory, *f* is the studied flight and BP is the best performer of the flow associated with *f*, we have:

$$KPI_2\ (f) = C_{model}(f) - C_{model}\ (BP) \qquad (9)$$

The national indicator is the aggregation of this score in the form of a sum of consumption for a given time period and for all trajectories in the French airspace.

c) KPI 3: *ANSP Fuel structural relative deviation*: this indicator aims to measure the impact of the airspace structure in terms of fuel consumption. It also allows monitoring the evolution of the environmental performance of the airspace following changes in its structure.

Each trajectory is studied by flow, the consumption associated with the trajectory is computed for the reference aircraft type corresponding to the associated aircraft group. The associated track distance is also computed. Then this consumption is compared to the consumption associated with a reference which would be a direct trajectory.

This direct trajectory is computed according to the type of operation as illustrated for a domestic flight in Figure 1. Either it is an international arrival or a fly over, and the radar plot of entry into the airspace will be considered as the first point, or the point located 4NM along the axis after take-off will be considered and 4NM will be added to the final distance. Similarly, the final point used to calculate the distance is either the point of exit from the airspace (international overflight and departure) or the point located 9NM on axis before landing and add 9NM to the final distance.

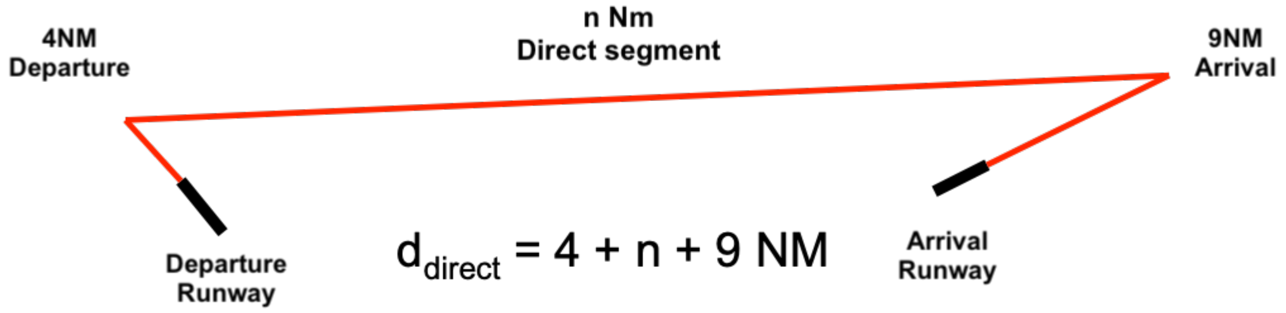

Figure 1: Example of a direct distance calculation for the case of a domestic flight. The distance of each segment is the geodesic distance, here represented by a straight line.

The indicator then calculates the average consumption of the flight per nautical mile, taking into account the weather conditions. Then, multiply the average consumption by the distance of the direct route to obtain the consumption of the direct route under similar flight conditions. Finally, the consumption of the flight is subtracted and divided by this estimated direct consumption. This gives a score which is a difference in % of consumption compared to a similar direct path.

Suppose that C_{ref} is the fuel consumption computed from the reference model, f is the flight studied, and d_f and d_{direct} are the distances of the trajectory and the direct, we have:

$$C_{ref}\ (direct) = C_{ref}\ (f) \times \frac{d_{direct}}{d_f} \qquad (10)$$

$$KPI_3\ (f) = \frac{C_{ref}\ (f) - C_{ref}(direct)}{C_{ref}(direct)} \qquad (11)$$

The national indicator is the aggregation of this score in the form of mean and standard deviation for a given time period and for all trajectories in the French airspace.

d) KPI 4: *Real fuel structural absolute deviation*: the fourth indicator aims to measure the equivalent of this ANSP structural deviation in terms of difference in kg or ton of fuel compared to the direct trajectory, taking into account the typology of the fleet.

Each trajectory is always studied by flow, the actual consumption associated with the trajectory is computed taking into account the aircraft type of the flight. It is then compared in absolute terms with the consumption of the direct trajectory of the flow, taking into account the same process as for the previous KPI. The score obtained corresponds to a difference in kg of consumption compared to the direct trajectory of the flow associated with the trajectory.

Suppose that C_{model} is the fuel consumption computed from the model corresponding to the aircraft type of the trajectory studied, f is the flight studied, and d_f and d_{direct} are the distances of the trajectory and the direct trajectory we have:

$$C_{model}(direct) = C_{model}(f) \times \frac{d_{direct}}{d_f} \qquad (12)$$

$$KPI_4\ (f) = C_{model}(f) - C_{model}(direct) \qquad (13)$$

The national indicator is the aggregation of this score in the form of a sum of consumption for a given time period and for all trajectories in the French airspace.

e) *Aggregation by type of operation and at local level*: The aggregations of the four national level indicators presented above can also be aggregated / broken down to a lower level of granularity to show scores on the four groups of operations:

- International departures;
- International arrivals;
- Domestic flights;
- Fly over operations.

In addition, these indicators can be computed for particular horizons or phases of flight to meet local needs such as those of airport hubs. They can be adapted and computed for specific enroute, approach and departure phases by taking into account circular areas around an airport or by taking into account the geographical limits of airspaces.

In particular, for the approach and take-off phases, these indicators can also be computed for a sub-trajectory noise metric (e.g. ANSP noise best practice relative deviation). The four indicators remain the same but would be applied to a noise integral instead of consumption. Finally, indicators will also be developed to allow the monitoring of energy atypicalities during the last nautical phase of the approach.

ANSP arrival performance at CDG

The objective of the project is to investigate the deployment of these kind of indicators at large scale to monitor performance over all the ANSP every day. As a primary study, we have focused on applying those indicators to evaluate the ANSP performance in the arrival phases at Roissy Charles de Gaulle airport.

In order to illustrate the use of these metrics and indicators, a study was conducted for arrival flights at Charles de Gaulle Airport (CDG). The data set is composed of radar trajectory for two week periods with a total of 8222 flights. The area considered is a circle of 100NM around the airport. We will focus on runway 26L, which was the main used during this period (4698 flights) and receives arrivals from each four entry points. Figure 2 illustrates lateral trajectories of runway 26L landings.

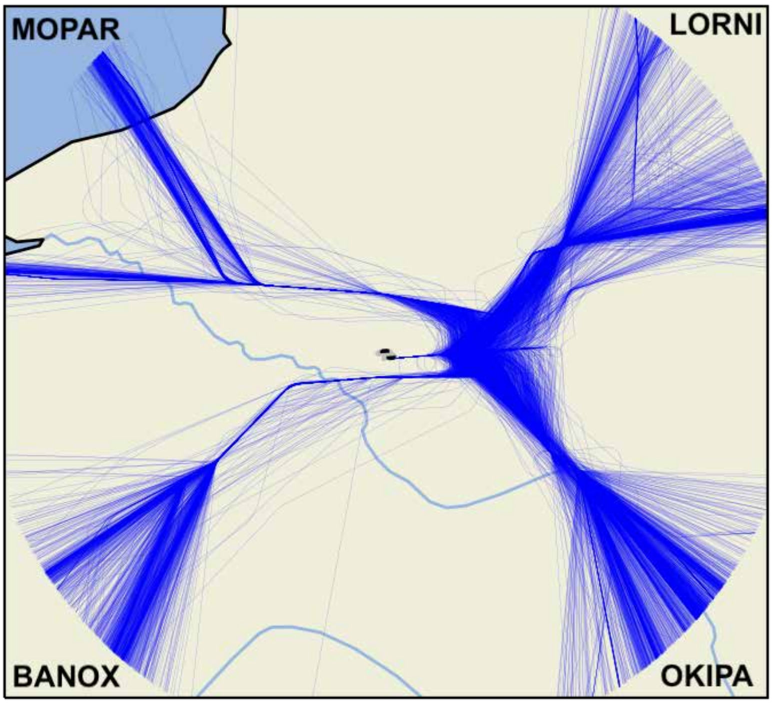

Figure 2: Illustration of longitudinal arrival flight trajectories at CDG airport runway 26L with the four flows from CTR entry points.

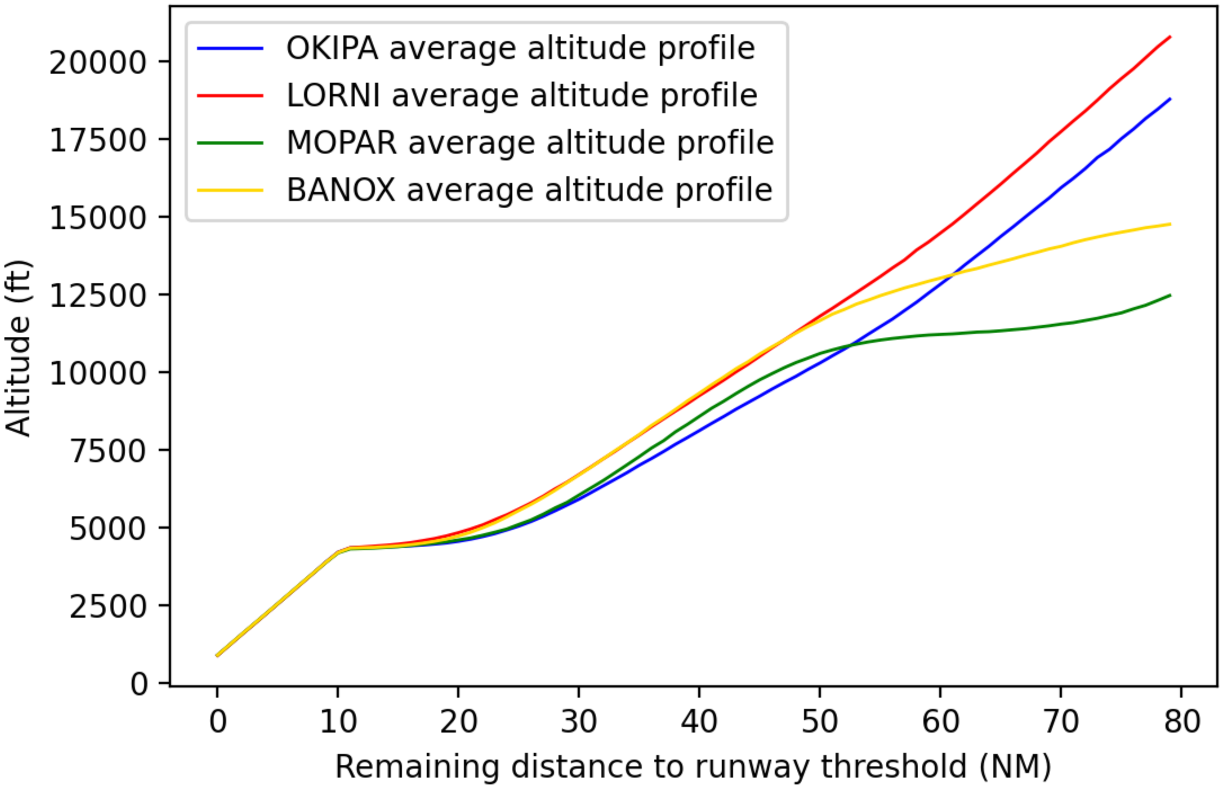

Figure 3: Illustration of average altitude profiles for arrival flows at CDG airport runway 26L.

A summary of the ANSP KPIs (KPI 1 and 2) aggregated by flow is presented in Table 5. We first observed that KPI 3 (relative structural deviation) is able to capture the structural impact of the downwind leg for both MOPAR and BANOX flows. It also captures the fact that BANOX has a larger structural deviation due to the shape of the downwind leg (KPI 3: 0.462 and KPI 4: 260 tons). With regard to KPI 1 (relative best practice deviation), we observe that the OKIPA flow has the worst score. If we compare the altitude profiles shown in Figure 2 with LORNI, which has a similar structural deviation score, we observe that the altitude profiles, illustrated in Figure 3, are generally lower for the OKIPA flow, and present longer level segments compared to the LORNI flow. Similarly, we observe that the BANOX flow is higher than the MOPAR flow in the average profile. Furthermore, the variability (standard deviation) of the LORNI and OKIPA flows in KPI 1 is higher than that of the BANOX and MOPAR flows. This implies a greater diversity in terms of lateral and vertical profiles, which leads to diversity in terms of fuel consumption. It highlights potential improvements, which could help to reduce the overall environmental impact; in particular by reducing the variability of altitude profiles and pushing these profiles towards the best performers.

Flow	Trajectory (#)	Distance NM (std)	KPI 1 (std)	KPI 2 kg/vol	KPI 3 (std)	KPI 4 kg/vol
OKIPA	1816	106.85 (4.51)	0.425 (0.203)	131.9	0.090 (0.046)	45.3
MOPAR	718	143.93 (6.78)	0.407 (0.157)	177.8	0.420 (0.065)	225.1
LORNI	1058	106.89 (4.35)	0.408 (0.200)	119.6	0.078 (0.041)	37.4
BANOX	1106	146.31 (7.44)	0.375 (0.153)	162.6	0.462 (0.074)	235.6

Table 5: Results of the two first KPI for arrival flights at CDG airport runway 26L. For KPI 1 and 3 the aggregated mean score for each flow is displayed first and the standard deviation is given between parentheses. For KPI 2 and 4 the sum of the consumption deviation is detailed in tons.

Discussion and conclusions

Discussion

In the presentation of machine learning models, we saw that the generalisation process could be improved. In particular, we consider three directions. Firstly, a potential normalisation could be carried out directly during training by normalising the flight data parameters with characteristic aircraft values, such as maximum airspeed or altitude, but also with characteristic fuel flows from the ICAO engine emissions database. By doing so, we might improve the generalisation performance of the model. Secondly, in the context where we have access to a small dataset for a particular aircraft type, we can apply an optimisation process to obtain the scaling coefficient instead of using the coefficient from the ICAO engine emission database. Finally, we can also imagine doing transfer learning from existing models with this small dataset, in order to re-train the existing models to improve their performances on the new aircraft type.

Regarding the indicators, a potential extension could be imagined to take into account other information such as weather conditions. As the consumption is computed with the actual trajectory, it inherently takes into account the effects of wind. This effect could be mitigated by adding a correction coefficient, e.g. the ratio between the distance of the trajectory on the ground (integral of the ground speed) and the distance of the trajectory in the air (integral of the true air speed). This coefficient could help identifying the intrinsic performance of an ANSP by removing the effects of wind.

Conclusions

This paper investigates the use of machine learning models to predict aircraft on-board parameters and to develop indicators and environmental metrics to assess ANSP performance. Neural network architectures from previous research have been extended to handle all phases of flight with relevant performance. A methodology for scaling model prediction using available engine information has also been detailed, showing promising capabilities.

A set of indicators has been proposed with two major axes: ANSP performance and global performance evaluation. These indicators are based on the definition of a best performer among traffic flows, and the estimation of direct trajectories. They aim to assess both inefficiencies in terms of best practice and airspace structure.

A first use case was illustrated at Roissy Charles de Gaulle airport, highlighting the capabilities of the methodology to monitor the environmental performance of ANSPs in the approach phases.

Future work will focus on the development and application of all indicators in different use cases such as door-to-door operations. The extension of this work to integrate noise aspect for arrival and departure operations is also being investigated. Machine learning models will improve the classical noise models by providing additional input parameters or thrust estimates that can then be used to feed the ICAO noise power distance models [31]. From these noise estimates, a metric can then be computed as a noise integral for each trajectory, and adapted to the indicators proposed in this paper.

The aim of this work is to deploy these analyses and indicators on a large scale for all operations in ANSP airspace. This will allow daily, monthly or annual monitoring of ANSP performance. Finally, further research could be conducted on the machine learning model to improve the generalisation process.

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Reducing Europe's aviation impact on climate change using enriched air traffic forecasts and improved efficiency benchmarks

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Abstract

Air Traffic not only faces the pandemic effects of a massive downturn in flight movements since 2020 but also a strong societal spirit of expecting significant ecological improvements to be made by the aviation industry, i.e., airlines, airports, and air traffic management. Since 2012, this industry is reporting its performance following the SES scheme, currently reference period (RP) 3 being active. To cope with these expectations, this paper presents a concept to enrich air traffic forecast data with emission data allowing to specifically benchmark ecological performance transparently and fair. We propose complementing current forecast data using the Enhanced Traffic Assessment System – ETAS and introducing the metric '3DE' addressing fuel burn and derived emissions based on initial flight plan data as filed by the airspace user per emissions referring to effectively operated flights including tactical ATC measures. We show that the developed concept performs well for a data sample focusing German airspace using the EUROCONTROL NEST simulation tool. We also show that the metric is highly sensitive to ATC activities and how this data is produced. We suggest introducing the '3DE' metric in future reporting schemes such as RP4, starting in 2024.

Motivation – ATS planning

Air traffic in Europe is currently managed by 38 individual air navigation service providers (ANSPs). These enterprises represent natural monopolies and are as such regulated through EU directives, recently with (EU) 2020/1627 to deal with the exceptional COVID conditions. With Implementing Regulation (EU) 2019/317, the European Commission laid down a performance and charging scheme relating to the Single European Sky (SES) directive: It addresses 29 States (27 EU member states, Norway and Switzerland) that are involved in the EU-wide performance target setting [1]. For selected metrics, those states have to report along the current reference period 3 (2020-2024). These indicators cover the key performance areas (KPAs) safety, environment, capacity, and cost-efficiency [2]. This being mainly unchanged since 2012 with the start of RP 1. However, it is expected that safety and environment KPAs will gain more importance in relation to the others, implying specific measures by political and operational decision makers. The significance of environment (and insignificance of capacity) is not only due to current political and social trends, but also to the predicted demand figures: As shown in Figure 1, only the maximum scenario, i.e. the highest increase in traffic demand, forecasts that traffic is on the pre-COVID level within the next four years, and thus at the end of the reference period (see also [3]).

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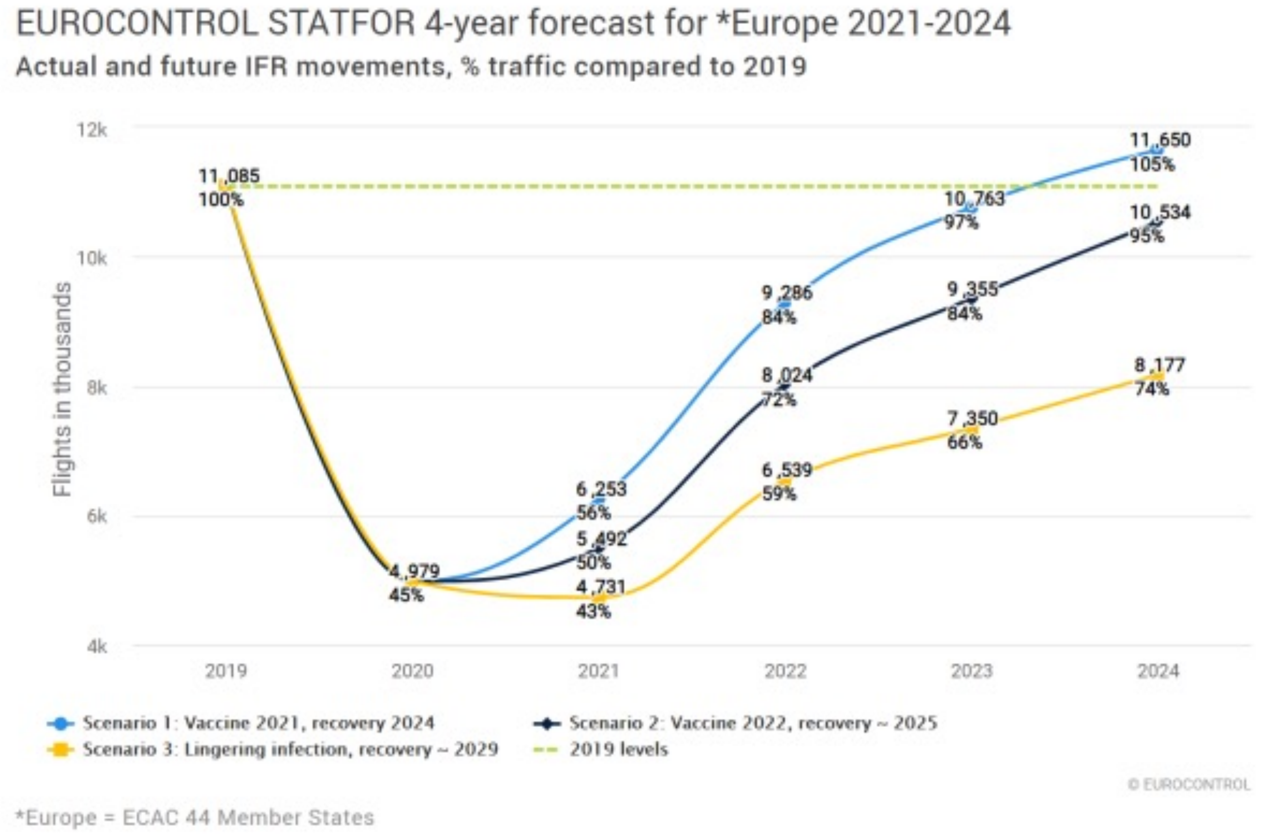

Figure 1: Expected Traffic growth 2020-2024 [4]

To mitigate the impact of climate change thus meeting Europe's ambitious carbon neutral target by 2050 [5] now requires significant improvements in coordinated measures particularly in the competing areas environment and cost efficiency, whereas the latter is increasingly impacted by environmental costs thus nested with the first. So far, environment related performance is assessed by a signal factor in RP3 – the average horizontal en-route flight efficiency (HFE) [6]. The HFE is expressed as a ratio of distances and is therefore an average per distance within a given airspace: All portions p of a flight f traversing an airspace j are considered, comparing flown (L) and achieved (H) distance as shown in (1).

$$HFE_j = \frac{\sum L_{fjp} - \sum H_{fjp}}{\sum H_{fjp}} \qquad (1)$$

Basically, the lower the HFE, the higher the additional fuel consumption and emissions produced. However, the HFE does not consider aircraft operating speed and so fuel consumption cannot not reliably be derived. In toto, HFE is hardly ecologically sensitive. In 2021, driven by the still limited amount of flight operations in Europe, the HFE achieved values between 98 and 94% (see Figure 2), depending on the selected reference. It should be noted, that the HFE may be referred to three different trajectory data [2]:

- The shortest constrained trajectory (SCR), not influenced by weather conditions or specific airline considerations, usable for monitoring purposes ('KES'). It sets the limits within which the airlines can optimize.
- The last filed flight plan trajectory, which may also be used for monitoring ('KEP'). The filed flight plan must always be at least as long as, if not longer than, the SCR.
- The actual trajectory (CPR) derived from surveillance data forming the key performance indicator ('KEA') which, apparently, is influenced by weather and tactical ATC routings, can only be assessed ex-post.

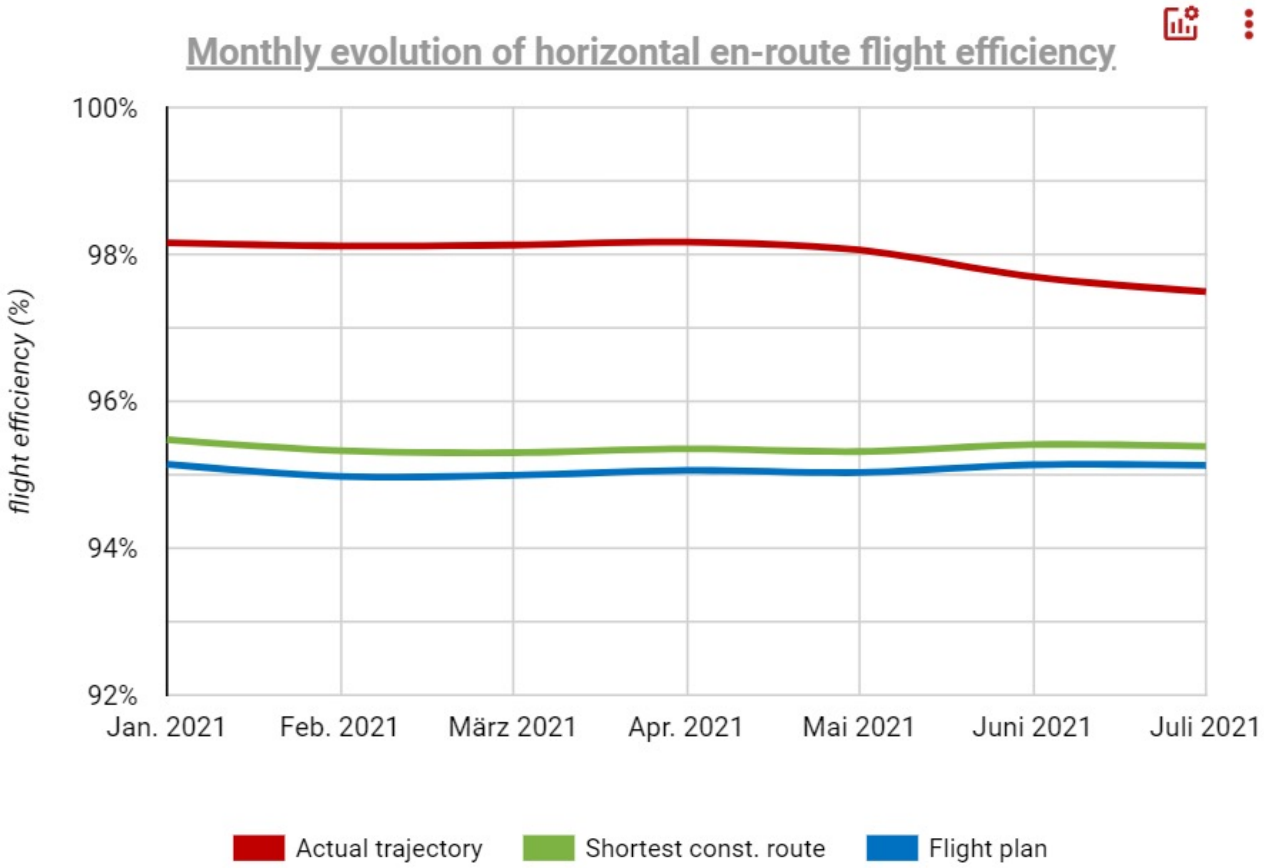

Figure 2: HFE per trajectory type, Germany State, 2021 [7]

Additional indicators for monitoring, aside HFE and mainly considered for general air traffic, consist of the

- effective use of reserved of segregated airspace as the ratio of initially requested allocated time for reservation and the final allocated time
- the rate of planning via available airspace structures calculated as the ratio of aircraft filing flight plans via such structures and the number of flights that could have planned through those structures.

Vertical profiling of initial or actual flight plans through metrics such as the vertical flight efficiency (VFE) is not considered to measure ANSP performance, yet. Nor reference figures for fuel consumption and emission exhausts are included. This leaves open, how capacity and consequently cost can usefully be forecasted and later assessed in air navigation service provision performance towards economic targets such as productivity or cost-efficiency. And this is a crucial factor, since improved VFE during climb (e.g., continuous climb operations, CCO) and descent (e.g., CDO) can save relevant amounts of fuel and emissions. Current VFE figures show on average one to two min inefficient level flight during descent and about half a minute during climb [8] in the EUROCONTROL area. As for an en-route VFE measure¬ment approach, current initiatives look at comparing the maximum altitudes as filed in the flight plan between a specific airport pair with the equivalent of flights between similar airport pairs, relying on a given AIRAC cycle[1].

Current air traffic forecasting

To allow for solid planning in operational ANSP performance, the EUROCONTROL statistical forecast (STATFOR) team provides a source for flight forecasting leading to network traffic scenarios in the near or distant future. The intent is to understand and mitigate risk, identify bottlenecks and anticipate the needs of airspace users [9]. The STATFOR publications comprise i. a. an industry monitor refreshed 10 times a year as well as a 7-year and a 20-year forecast to provide comprehensive future pictures of anticipated traffic development for the next years to come. Although forecast periods altered in the past, we focus on the 7-year forecast since it is used to predict ANSP needs in terms of ATCO staff planning, currently the main cost driver in air traffic management (ATM), published two times a year (spring and autumn forecasts).

We showed in [10], that current traffic forecasting reports for Europe (EUROCONTROL Statistical Reference Area, ESRA) are far too generic to effectively foster cost-efficiency as anticipated. As an example, STATFOR metrics such as the confidence interval (CI) expressing the range of expectancy of the number of flights per state or airspace region in the future, represented by different scenarios, inhere significant uncertainty (the CI being large) on resource and cost planning. We found that e.g., the spring forecast report 2019 implied a system-wide cost uncertainty of 399 Mio. Euros. In particular, the German, Spanish and French Air Navigation Service Providers were affected this way by cost uncertainty of > 50 Mio. Euros, each. We could also show the CI being matched in the minority of cases (33%), only – consequently 64% of the ANSPs facing a poor forecast quality. In addition, we proved that a low prediction quality impacts negatively, statistically significant, ANSP performance (delay and productivity).

Despite unavoidable random errors and noise (such as political or economic crises) inherently hampering forecast quality, the results motivate for researching alternative forecast quality indices. In connection with the paradigms discussed in section 1, we believe that such an upgrade candidate should merge the KPA environment and cost-efficiency. The next section recalls selected tools in Europe to potentially support that activity.

[1] *A year is typically split into 13 AIRAC cycles, timely linked to the update rate of the European Route Availability Documents (RAD), part of the European Route Network Improvement Plan (ERNIP).*

Selected tools to predict and assess traffic pattern and trajectories

The following list of presented tools and software does not claim for completeness but was selected along the very special function focus of working on Network Manager air traffic data.

NEST

Air traffic forecast data in Europe are generated by the Network Manager or single ANSP typically using the Network Strategic Tool (NEST) which itself relies on datasets provided by EUROCONTROL at the end of each AIRAC cycle, describing the consolidated pan-Euro¬pean airspace and route network, the traffic demand and distribution as well as the STATFOR traffic forecasts. It generates future traffic samples using traffic growth forecasts provided by STATFOR. Airport capacities and curfews can be used to constrain traffic growth. Basically, it refers to expected city pair connection frequencies and is as such a scenario-based modelling tool.

For the approach presented in this paper, we rely on NEST generated input data to grant operational compatibility of our results to existing data.

IMPACT

IMPACT is said to provide fuel-burn, noise, and emission calculations. It includes a common input data processor which calculates detailed 4D trajectories and fuel consumption for user-defined aircraft operations. These trajectories are then enriched with noise and emission estimations [11,12]. The authors could not test IMPACT so far due to license issues. This is a current assessment activity at TU Dresden.

SAAM

The system for traffic assignment and analysis at macroscopic level (SAAM) is said to be an integrated system for network-wide or local design, evaluation, analysis and display of air traffic, civil/ military airspace and TMA scenarios. SAAM can be used for operational planning purposes to optimise strategic traffic flows, to design the route network and airspace, to analyse past and future traffic flows, and to display and compare projects. It includes airspace design, calculation of 4D flight trajectories, airspace analysis (loads, flight efficiency, route charges, queries, fuel consumption/gas emissions, etc.), a simplified ATC simulation, an airspace visualisation and 3D animations [13]. For the same reason as for IMPACT, the authors cannot comment on the true capabilities of SAAM.

ETAS

The Enhanced Trajectory Assessment System (ETAS) has become operational in 2016 at the German ANSP DFS - Deutsche Flugsicherung around an initiative of a party of German airlines united as ‘Optimised Flying Working Group’, tending to minimize their ecological impact during operations. ETAS is a post-flight trajectory assessment tool. Historically, it has been developed to enable various kinds of performance benchmarking activities such as per-flight fuel efficiency and emissions, aircraft performance/ deviation estimation, continuous climb/ descent operations, cruise altitude and cost index selection, and trajectory-based noise mapping.

Figure 3: ETAS Data processing input-output model

Though ETAS was first targeted to support ANSP, airports, and government organizations, ETAS can now, in its third release, be re-configured to also meet airlines' flight planning and inflight decision support needs: Optimizing vertical profiles and routes, dealing with meteorological uncertainties, and enhancing existing tools and solutions for flight planning, ops control, and electronic flight bag (EFB) flight deck applications. Aircraft performance is modeled using EUROCONTROL Base of Aircraft Data (BADA). With Release 3.0, ETAS allows for adopting existing BADA models to reflect equipage details, such as retrofit winglets, or even individual aircraft performance levels. Likewise, completely new aircraft models can be introduced by means of calibration with customer-supplied flight data. Figure 3 depicts the workflow.

Improved performance measurement

Along the technological path formulated with the tools listed above and stated as motivation, the approach presented in this paper intends to bridge the KPA environment and cost-efficiency by enriching traffic forecast with emission estimates thus providing transparent and sensitive metrics, which could complement the data set to be used in RP4 of the performance scheme. Basically, the system design consists of a twofold loop using ETAS for the enrichment process as depicted in Figure 4: While the first loop (upper part) enriches and improves ex-ante the last filed flight plan data (KEP, see section 0) to provide an estimated performance respectively emissions and cost baseline, the second loop (lower part) evaluates ex-post, so after performance delivery, the actual (recorded) flight plan data (KEA, see also section 0). Equivalent to equation (1), we compute the operational cost and environmental efficiency by quoting effectively exhausted emissions linked to the corresponding trajectory data set and reference (initial) emissions. The following equation results by considering all portions p of a flight f traversing an airspace or a single city pair *j*, comparing 'actual' trajectory-based emissions (A) and 'initial' trajectory ones (I) as shown in (2).

$$3DE_j = \frac{\sum A_{fjp}}{\sum I_{fjp}} \tag{2}$$

The units applied to 3DE can be fuel consumption or CO_2 emissions as central indicator, used in the present paper. It can however be extended to all greenhouse gases (GHG) with a different global warming potential (GWP) and persisting for a different length of time in the atmosphere, using CO_2 equivalents in equation (2).

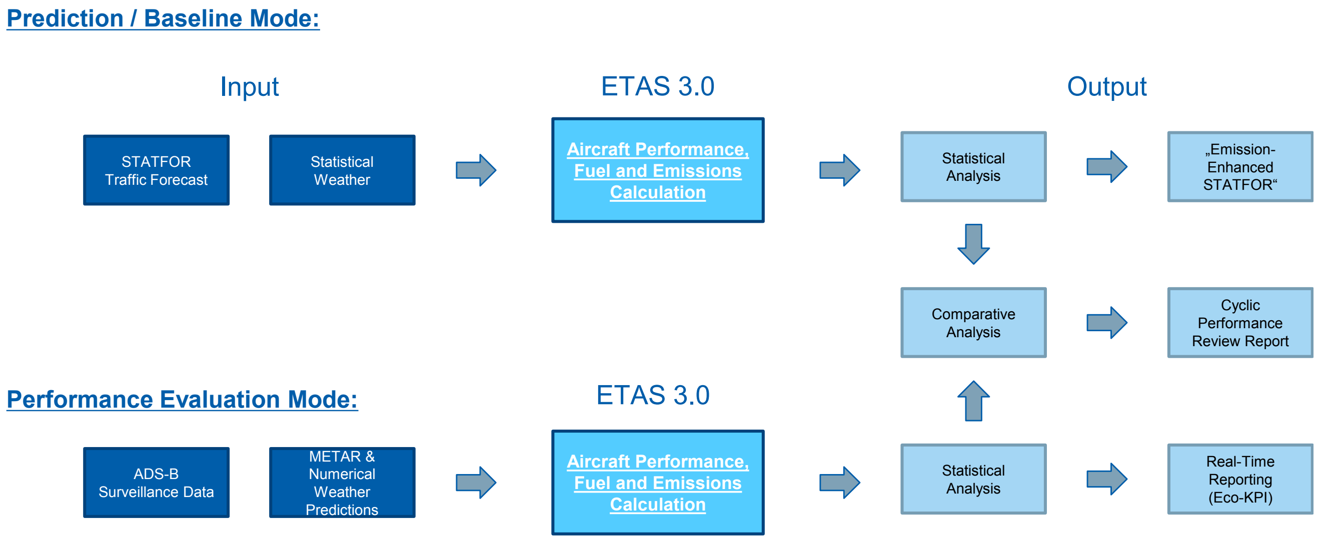

Figure 4: Estimating environmental 3D Efficiency (3DE) based on NEST traffic forecast data using aircraft performance models

We achieve – by using such an enriched data set in traffic forecast – a coupled cost-efficiency and environment performance assessment relying on additional metrics such as the Fuel Consumption index, the NO_x index, the CO index and more. All these additional indexes allow direct conversion to European emission scheme metrics and political target values along the European Green Deal initiative of climate neutrality by 2050 [5].

Enriched NEST Data Study

Data presentation

The following section describes the concept implementation with an exemplary use case relying on NEST data for the European airspace, i.e., for a set of selected city pairs to cover a diversity of aircraft types, track headings and leg lengths and evaluate the sensitivity of the output across various pairs. The data has kindly been provided by DFS Deutsche Flugsicherung [14]. Pre-processing of NEST Data

Pre-processing of NEST Data

Pre-processing of both data sources (initial and actual trajectories, see Figure 6) is necessary to allow for reliable flight performance calculations, namely coping with requirements to allow correlation of weather data with model-based smoothing of the trajectories, so to iron out inconsistencies in ground speed determination. We conclude that the reason for it lays in a coarse-grained depiction of aircraft motion as intended for network operations planning and not imitating radar tracking quality. The required performance calculations entail applying kinematic models (BADA, ETAS) and gridded weather data from national meteorological services.

We start explanations on the smoothing after a short look into the dataset itself: As can be seen from Figure 6 (top), the ‘initial’ flight plan, also denoted FTFM or M1 trajectory and representing the last filed ATC flight plan, already contains a rough vertical profile following ICAO Doc. 4444, Appendix 2-2 [15] standards such as initial cruise flight level, Top Of Climb, en-route step climbs, Top of Descent and an apparently uninterrupted descent due to a lack of further details. The lateral track is based on AIRAC cycle specific waypoints. All over, the initial flight plan is supposed to hold more horizontal flight inefficiency, in line with Figure 2, than the ‘actual’ (flown) track, also denoted CTFM or M3 trajectory, where the minimum should equal the SCR, not considered here (see equation (1)) and depicted in Figure 6 (bottom). Contrarily, the ‘actual’ trajectory is being updated as the flight progresses according to pre-set NEST update criteria (thresholds) such as

lateral offset	> 10 NM
vertical offset in cruise	> 400 ft
Time offset	> 1 min
vertical offset in climb/ descent	> 1,000 ft

Table 1: NEST update criteria for ‘actual’ trajectories

Updates are always matched to nearest waypoints of the given AIRAC cycle, which may, especially for issued ‘directs’ (DIR TO) result in faulty nearest-neighbor match-making, see Figure 5 and compare with Figure 6 (bottom):

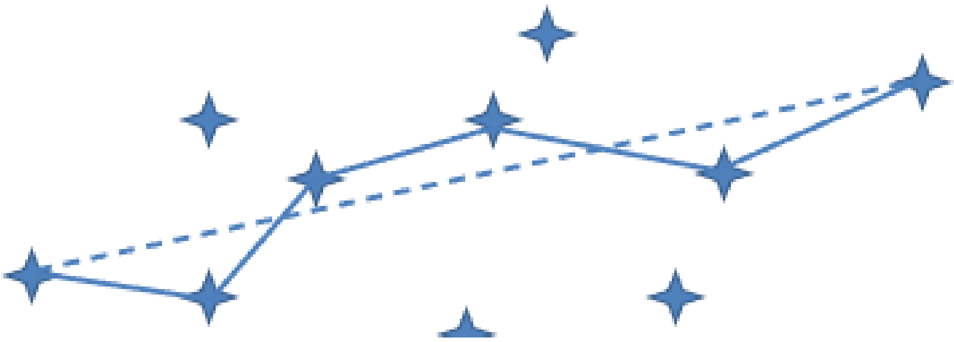

Figure 5: Artifacts inserted in NEST ‘actual’ trajectories due to pre-set thresholds and AIRAC cycle specific waypoints

Kalman filtering of motion data

We have been using an unscented Kalman filter for smoothing, proven for his excellent performance [16], with aircraft motion being modeled as a 3D point mass with a heading and lateral turn rate, both a lateral and a vertical velocity and additionally a lateral acceleration. If reduced to the 2D space (as done for robotics), this is commonly referred to as ‘unicycle’ kinematics.

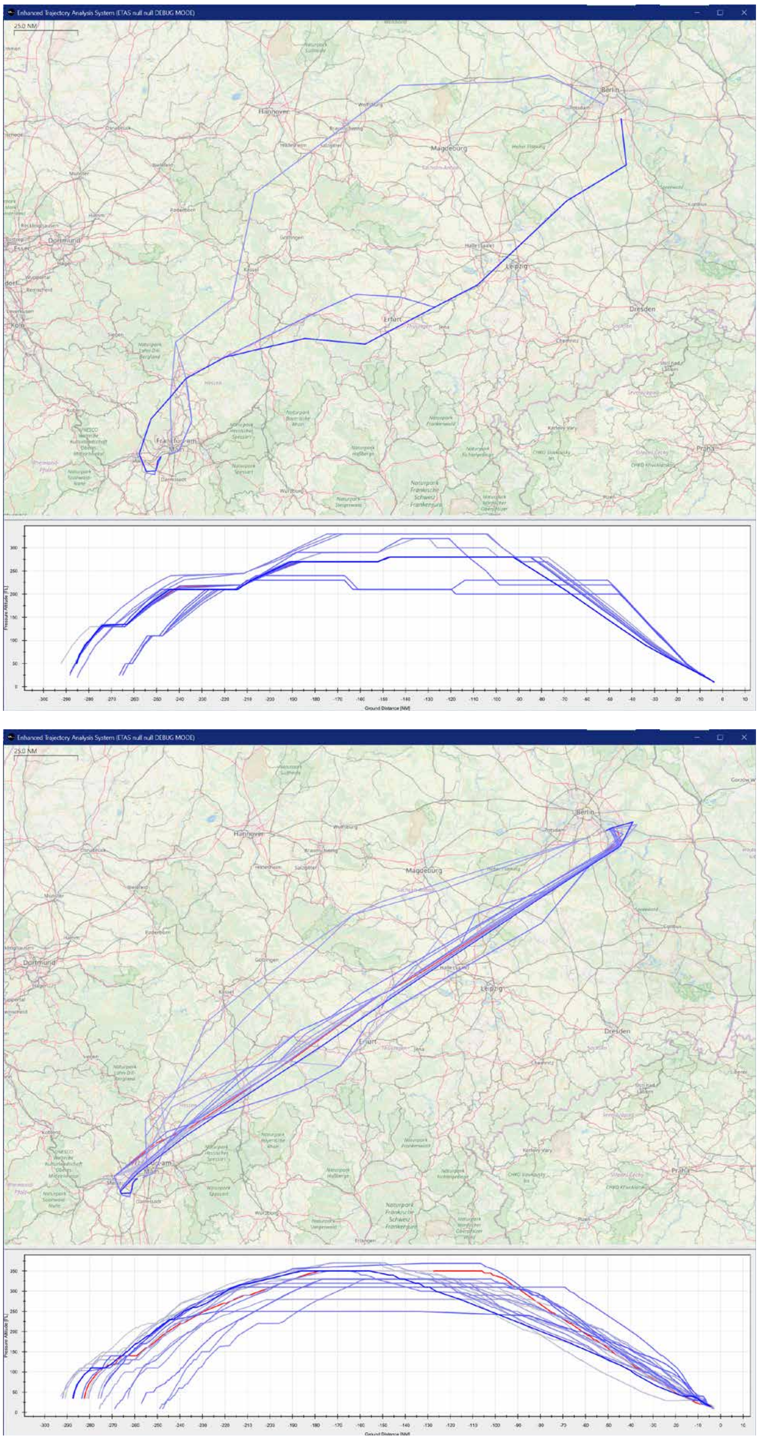

Figure 6: Use Case: Initial (top) and actual (bottom) trajectories taken from NEST, selected city pair EDDF-EDDB

Through heading changes and accelerations, nonlinear properties require using an extended or unscented Kalman filter (EKF, UKF). The aircraft state is finally given at any point and time by:

$$x = (\varphi, \phi, h, \dot{h}, \psi, \dot{\psi}, v, \dot{v}) \qquad (2)$$

The elements are respectively latitude φ, longitude ϕ, altitude h, vertical speed $\dot{h}$, heading (azimuth) ψ, horizontal turn rate $\dot{\psi}$, lateral true velocity v, and lateral acceleration $\dot{v}$. Differences in mathematical and nautical notation of angles, unit and geodetic coordinate conversions require special attention, but are widely supported across software packages nowadays.

The model for recursive state evolution for a given time interval dt in the range of 1- 10 sec is:

$$\bar{v} = v_{-1} + {}^{dt}/_{2} \cdot \dot{v}_{-1} \qquad (3)$$

$$\bar{\psi} = \psi_{-1} + {}^{dt}/_{2} \cdot \dot{\psi}_{-1} \qquad (4)$$

$$\varphi = \varphi_{-1} + Proj\{dt \cdot \bar{v} \cdot \cos(\bar{\psi})\} \qquad (5)$$

$$\phi = \phi_{-1} + Proj\{dt \cdot \bar{v} \cdot \sin(\bar{\psi})\} \qquad (6)$$

$$h = h_{-1} + dt \cdot \dot{h}_{-1} \qquad (7)$$

$$\psi = \psi_{-1} + dt \cdot \dot{\psi}_{-1} \qquad (8)$$

$$v = v_{-1} + dt \cdot \dot{v}_{-1} \qquad (9)$$

The variables $\bar{v}$ ‘effective velocity’ and $\bar{\psi}$ ‘effective heading’ are calculated as triangle integral following equations (3) and (4). The vertical speed, lateral turn rate and forward acceleration are assumed to be constant in the state prediction model but are corrected by successive measurement updates (filter feedback). In this sense, equations (5) to (9) formulate the model of aircraft motion.

Furthermore, a projection function (denoted Proj{·}) to convert from cartesian North, East earth-fixed coordinates to latitude, longitude referring to the WGS84 ellipsoid is applied. This function has shown robustness against tracking error conditions. Small faults in the geodetic projection function are therefore acceptable.

The resulting tracking filter is parameterized through setting the measurement covariance vs. the process covariance matrices. We assume fully independent processes, hence only assigning the diagonal matrix components. For the measurement, we make assumptions about GPS (40 m standard deviation as lateral uncertainty), barometric altitude (1 m standard deviation vertical uncertainty), differential GPS speed determination (1 m/s standard deviation uncertainty). For the process uncertainty, we further consider the maneuverability of the aircraft, but work has shown that a trade-off is required at this point, as only much lower uncertainty would lead to effective track smoothing. The trade-off between smoothness and accuracy is achieved by allowing a either low or high lateral acceleration $\dot{v}$ on the process uncertainty model. Also, interdependencies between lateral vs. velocity tracking exist. In Figure 7, we exemplarily show the effects of over- and underestimating the acceleration and the effects of smoothing both lateral motion (upper part) and velocities (lower part):

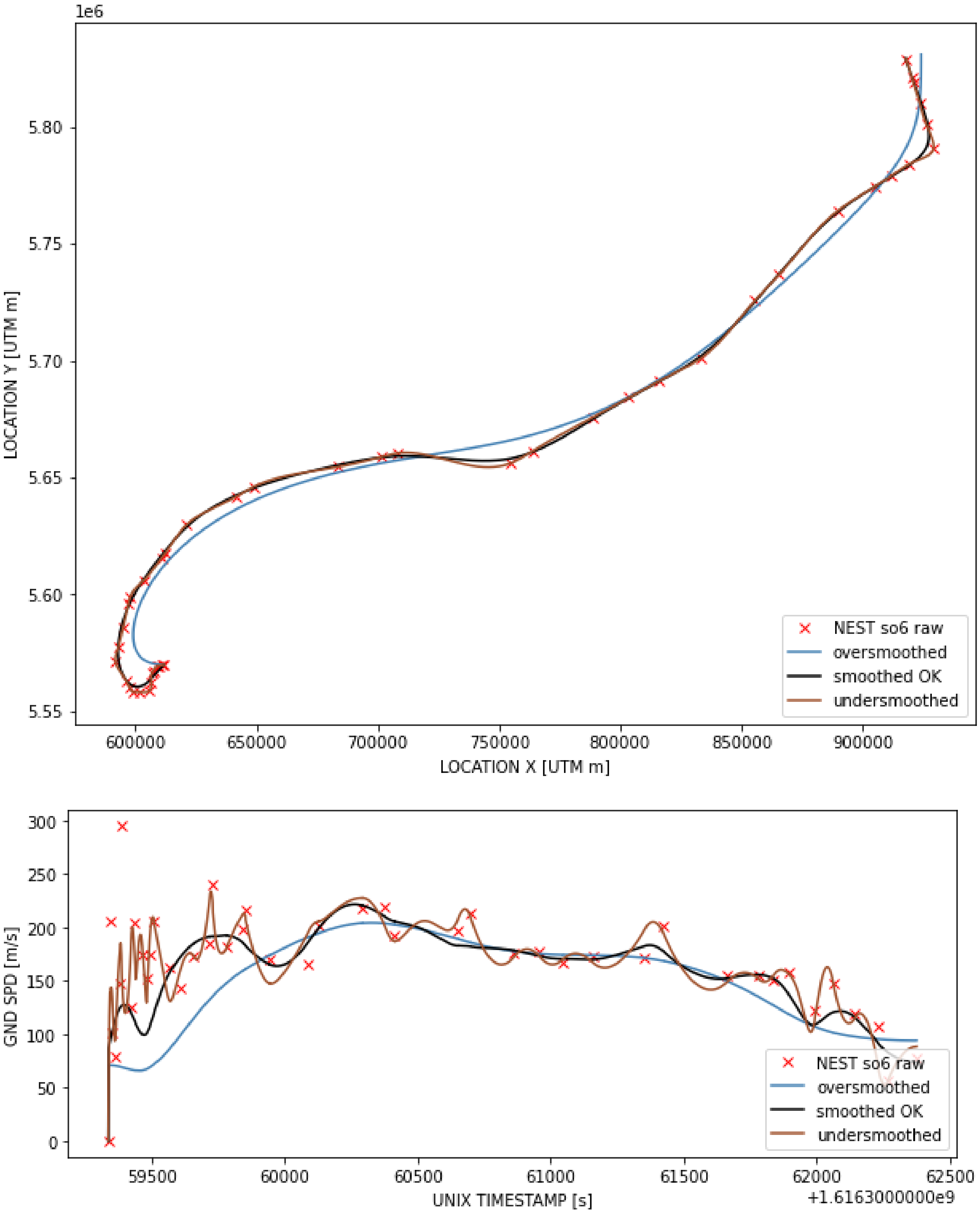

Figure 7: Raw vs. differently smoothed lateral trajectories and speed profiles for an example flight EDDF-EDDB

ADS-B data based verification

A third dataset was built for verification purposes for the ‘initial’ and particularly the ‘actual’ NEST trajectories using OpenSky Network ADS-B data [17]. This step was considered important as the ‘actual’ trajectories are deemed to still contain virtual ‘detours’ from match-making to AIRAC waypoints along the setting listed in Table 1 that do not represent real flight behavior. It should well be noted that this data set is not intended to be part of the presented concept but used to prove scientific soundness of the conclusions drawn. Especially during the COVID-19 low traffic period in early 2020, on which the used traffic sample relies, many issued long ranging ‘directs’ were apparently issued and cleared by ATC.

This preposition can be followed by inspecting Figure 8: Kalman-smoothed NEST ‘actual’ trajectories (top) are compared to ADS-B track data (bottom). From the lateral plot, we conclude that while ADS-B data shows various straight, long directs covering the entire en-route segment, the ‘actual’ trajectory data imply that intermediate waypoints were passed. Likewise, the vertical profiles equal each other rather poorly: The ‘actual’ trajectories imply much larger horizontal climb segments than what show ADS-B data:

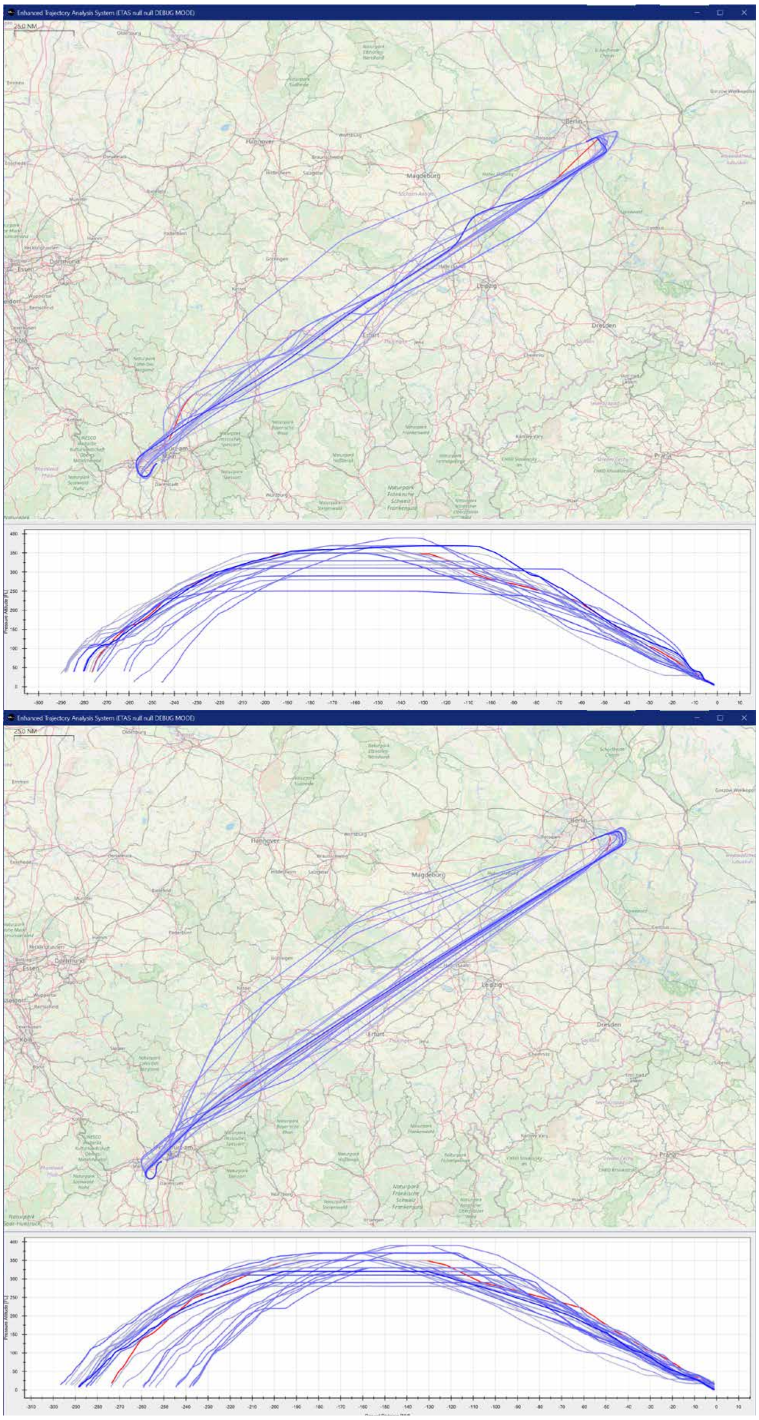

Figure 8: Smoothed actual flight plan (top) vs. ADS-B validation data (bottom); all EDDF-EDDB city pair flights

From this we conclude that the thresholds for actual trajectory updates currently implemented in NEST as listed in Table 1 are strong driver for poor representativity and should be upgraded if NEST remains the data source for the presented performance assessment concept.

DWD weather data correlation

To include weather phenomena such as the wind in aircraft motion data and significant weather conditions (e.g., ISA deviation), gridded weather data called 'WTQ2' was taken from German meteorological office (DWD) sources, again gently provided by the German ANSP DFS. The data rely on numerical weather prediction, i.e., short to medium-term simulation incorporating all available measurements.

The obtained dataset is a reduced, i.e., tailored aeronautical weather data subset titled WTQ2, which stands for Wind, Temperature, QNH (pressure altitude) plus 2 more values (namely, density and humidity).

To bring WTQ2 data down to the required resolution needed for the data correlation, we interpolate the grid data according to space and time using a 4D bilinear interpolation. Various trials with alternate interpolation techniques such as Ordinary Kriging are still being studied by the authors. The wind component was interpolated for the u and v components separately.

Given the coarse-grained motion data, ISA conditions can form a simple and effective alternative in pre-flight performance prediction mode, depending on the amount and quality of weather data contained in the NEST operator-filed 'initial' trajectory data. As a substantial amount of uncertainty may exist, we aim at minimizing the potential uncertainties of weather prediction.

For post-flight performance assessment using 'actual' trajectory data (NEST or – for validation – ADS-B), high-quality weather data may be needed. A missing or faulty wind component can propagate errors in the motion description: Resulting faulty, excessive airspeeds would potentially lead to an overestimation of drag forces and consequently excessive fuel flows downstream.

If provided and considered in the calculation, the weather influence alone can impact positively (e.g., tailwind) or negatively (e.g., headwind) and hence biases the computed ANSP performance. This effect has been studied for the NEST data sample under consideration and was, despite all the listed hazards, found to be rather small and most importantly unspecific, as can be seen in Figure 9.

Over the various origin-destination pairings contained in the dataset, the average fuel used does not change for both scenarios (dots on the diagonal, up, upper part), whereas the variance increases, and certain north-south pairings see savings while most other see slight penalties. The authors cannot exclude an artefact of the used dataset, yet. This will be subject to further investigation.

For now, we conclude that the effects and the importance of weather and its data representation are more relevant for longer distance flights, while the influence of ATC on short flights, e.g., to accommodate weather changes, is rather limited. To summarize, the overall effect of weather does not seem too relevant for the presented concept and may be neglected.

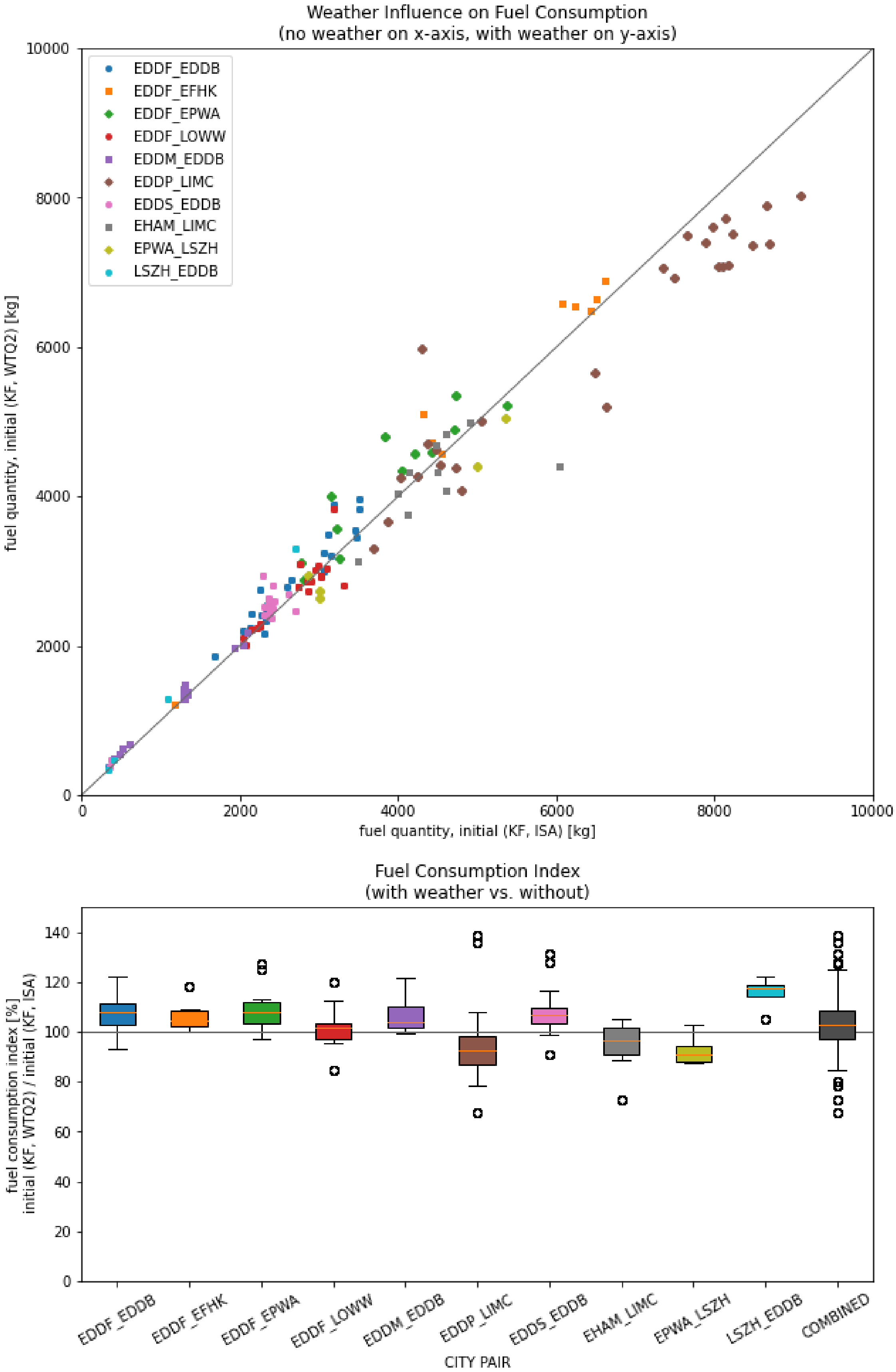

Figure 9: ‘Initial’ trajectory calculated with and without WTQ2 weather – no severe effects

Results

To show how the 3DE performance indicator would work in practice, the kinematic flight performance model (termed total energy model, TEM, in BADA) has been applied to the various Kalman-filtered trajectory data sets. This effectively determines the thrust, the remaining vector forming the force equilibrium in flight. Fuel flow is then determined using BADA's or the ETAS engine model (see Figure 3). With WTQ2 data included, and ADS-B data used for model verification, the following comparison results for the various city pairs forming the use case. For all the subsequent calculations, WTQ2 weather conditions were used for both prediction and assessment, and aircraft reference masses according to EUROCONTROL BADA4 were applied. These assumptions, even though injecting some uncertainty in the model, grant comparability between ATM units, judged important for a practical application.

Figure 10 shows the 'truly achieved' (in ADS B accuracy) 3DE performance for all studied city pairs, however, with significant variations.

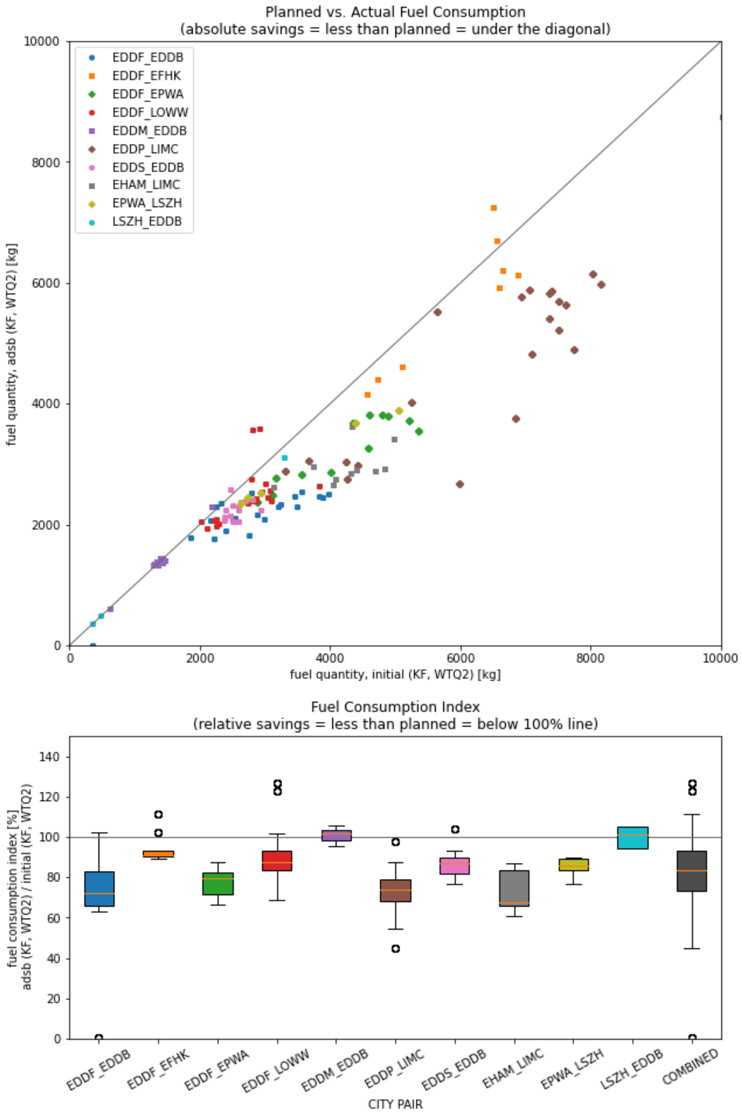

Figure 10: NEST 'initial' trajectory calculated with WTQ2 weather and compared to smoothed ADS-B data

De facto, the results imply, that the involved ANSPs overperformed the baseline (initial trajectories) versus ADS-B data-based trajectories, graphically expressed by the dots laying below the diagonal, moved into the 'savings zone', or below the 100% marker in the box plot respectively.

All city pairs combined, only approx. 85% fuel is being used compared to baseline, indicating some 15% savings. Individual city pairs offer even more favorable savings (e.g., flights from the north into LIMC) and different routes and/ or aircraft types are distinguishable (e.g., for EDDP-LIMC, chocolate color, forming two clusters in the scatter plot). To demonstrate the effect of NEST 'actual' trajectories only partly reflecting real traffic behavior (see Figure 5), based on the correction thresholds shown in Table 1, the following Figure 11 shows the same 3DE analysis comparing the baseline (initial trajectories) now versus actual trajectories, KF smoothed, taken from NEST.

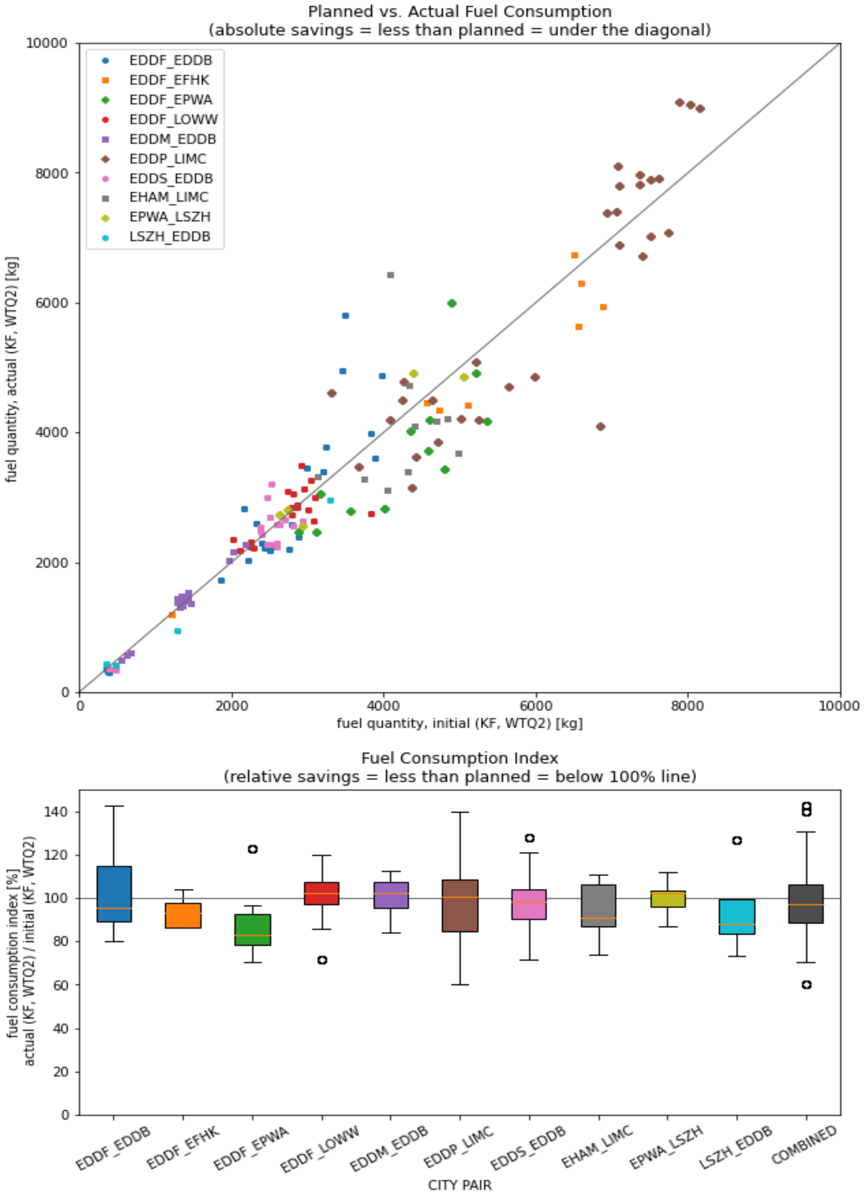

Figure 11: NEST 'initial' trajectories calculated with WTQ2 weather and compared to NEST 'actual' trajectories

We see much less distinction between both data sets, resulting in a combined 3DE around 1,0 (see outer left box plot and Table 2: The computed 15% savings in fuel consumption would not have been accounted for if using NEST 'actual' flight plans. However, the variability in the performance per city pair remains visible and obvious.

City Pair	ADS-B	Actual
EDDF-EDDB	74.28 %	103.56 %
EDDF-EFHK	93.81 %	93.35 %
EDDF-EPWA	77.11 %	86.77 %
EDDF-LOWW	88.31 %	101.30 %
EDDM-EDDB	100.89 %	100.96 %
EDDP-LIMC	72.40 %	98.40 %
EDDS-EDDB	87.18 %	98.29 %
EHAM-LIMC	70.78 %	96.28 %
EPWA-LSZH	83.88 %	100.19 %
LSZH-EDDB	99.58 %	94.28 %
COMBINED	82.51 %	98.38 %

Table 2: 3DE figures for 'initial' vs. ADS-B resp. 'actual' trajectory with selected city pairs, and all pairs combined

We conclude, that for those city pairs showing rather poor 3DE values such as e.g., EDDM-EDDB, the airspace and sector structure may inhibit lifting ecological potential by the ANSP on tactical level. This should be subject of a tailored review by the ANSPs responsible for every identified city pair. Of course, this is an initial assumption, only and should be subject to a thorough operational expert review. As an additional evaluation step, disaggregation of the 3DE figures from city pair to FAB or single ANSP can be easily derived and used for cross comparison.

Findings and conclusion

As elaborated, the European ANSPs' staff/ labor cost planning rely on the 7 -year STATFOR forecast air traffic refreshed twice a year [18]. These data are disaggregated by the Eurocontrol Network Manager from purely horizontal city pair legs as provided by STATFOR using the NEST [19] tool. Debate has been raised to what extent this forecast might be enriched to cope with the growing relevance of a sustainable aviation system [20] and legal requirements from RP4.

In this study, we propose to link the highly granular and validated aircraft performance and emissions assessment tool ETAS [21] developed by GfL and operational at DFS since 2016, complemented with initial flight plan profiles to enrich NEST forecast data with a predicted emission figure per sector, State or ANSP for a given forecast period. We suggest the metric '3DE' to be used: The baseline, based on 'initial' trajectory data, will be compared to the 'actual' trajectories (KEA) using ETAS. For validation purposes, we added surveillance data (SSR Mode S/ADS-B) such as FANOMOS [22] and data from OpenSky [17] from the same time frame. By comparing baseline to actual operations, we derive the 3D (altitude plus horizontal motion) environmental efficiency called '3DE' achieved per region and time, which is usually impacted by tactical ATC advised detours, time, speed and altitude constraints. We could show the remarkable sensitivity of the selected baseline (initial trajectories) and throughput (actual trajectories) on the output: We suggest keeping NEST as the input source, while adopting the current update mechanism to build 'actual' trajectories (see Table 1). This way, even small achievements brought to the system by tactical ANSP measures can be made transparent.

As a result of the data availability and based on what we have learned about STATFOR's approach to forecast demand, our analysis refers to city pairs. However, to allow for performance benchmarking, we suggest aggregating the data. As an example, personnel decisions (such as staff recruiting and rostering) are often made by the ACCs. Long-term financial planning involves the ANSP level. FABs publish performance plans and monitor their performance. In a further study, we will investigate on how to aggregate the results for macrolevel investigations. This will allow direct application of our presented concept on pan-European level and to complement official reports such as ACE and PRR.

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Towards limited impact on environment

Jean-Michel Edard[a] *and Ilona Sitova*[a]

Introduction

Whilst medicines and vaccines are being developed globally at an astonishing rate, the consequences of the Covid-19 crisis are far from over. Traffic demand is not forecast to recover to 2019 levels for several years, meaning it is the perfect time to consider what significant evolutions may be needed to face the new challenges of climate change and its relationship with Air Traffic Control.

During the latest 30 years, capacity has always been afforded primacy over environmental concerns, in spite of the consequences operational measures have on fuel burn, emissions and therefore climate impact. In the same way, charging rules have also negatively influenced airlines routing strategies, often leading to longer route segments to reduce the impact of these charges, but generating more fuel burn and CO2 emissions as a consequence. Therefore, in-depth analysis is necessary to highlight interdependencies between environmental KPAs and those KPAs which are detrimental to the environment, and contributing to climate change.

This paper highlights key challenges linked to the environmental role of ATC, analyses the main causes, and the impact on daily operations as well as on ANSPs strategic planning. Recommended mitigation measures such as flight route length for upper or lower airspace, vertical constraints and contrails are addressed in order to deliver more environmental efficiency. The paper concludes with listing trade-offs, measures along with an associated prioritisation with the aim of identifying the main areas of future research. The shortest or cheapest routes, are not always the most fuel-efficient ones, and might have an impact on climate. Solutions should be developed to improve procedures, and to limit the impact of ATC on climate change and will require deployment on short-, mid- and long-term horizons.

What ATC procedures have the greatest impact on the environment?

HFE: Horizontal trajectories

Measured as a percentage of route extension in comparison with the achieved distance (PRU Concept), FABEC HFE performance has improved to reach more than 97% efficiency for actual trajectories (KEA indicator), and more than 94% for filed trajectories (KEP indicator), as shown in figure 1 (dated from May 2021).

Between two airports, it is not possible to fly on a direct course. TMA Procedures, traffic segregation to ensure safety or circumnavigate military areas, political borders, adverse weather or a country's unit rates will still contribute to a certain horizontal flight inefficiency.

Many projects have been implemented in recent years to reduce flying or filing distances, such as FRA

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[a] FABEC Standing Committee Environment.

development throughout Europe, or RAD relaxations during COVID crisis. However, these indicators do not fully reflect the genuine performance of an ANSP, simply because some influencing factors such as weather, military activity or specific airline preferences are not within an ANSP's control. As such a new indicator is needed.

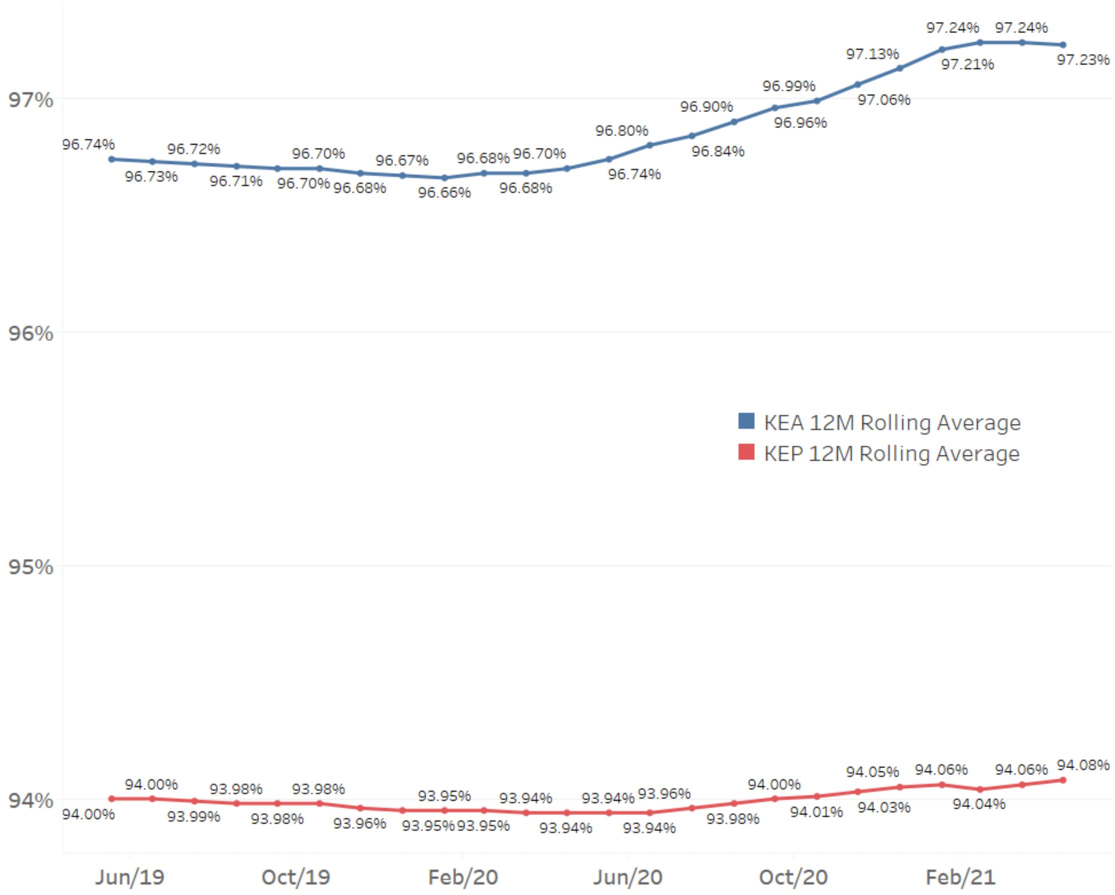

Figure 1: Rolling KEA and KEP indicators

Nevertheless, any new connection which improves a flight's efficiency, saves fuel and CO2 is welcome, especially when we know that an aircraft consumes between 6 to 11 kg of fuel per NM (between 18 to 34 kg of CO2), depending on the type of aircraft.

VFE: Vertical trajectories

Measuring vertical flight efficiency is not that simple. Methodologies used by the PRU or by NM's NEST tool are regularly used to assess VFE, however, the optimum level for a single aircraft type can vary significantly according to its weight, to winds or turbulence, therefore only a rough estimate can be generated by these tools.

As long as AO fuel data remains unknown, reliable vertical performance indicators will be difficult to set up. As an example, PRU developed a vertical assessment which compared a city-pair with constraints to one with a similar leg distance but without the constraints (see figure 2).

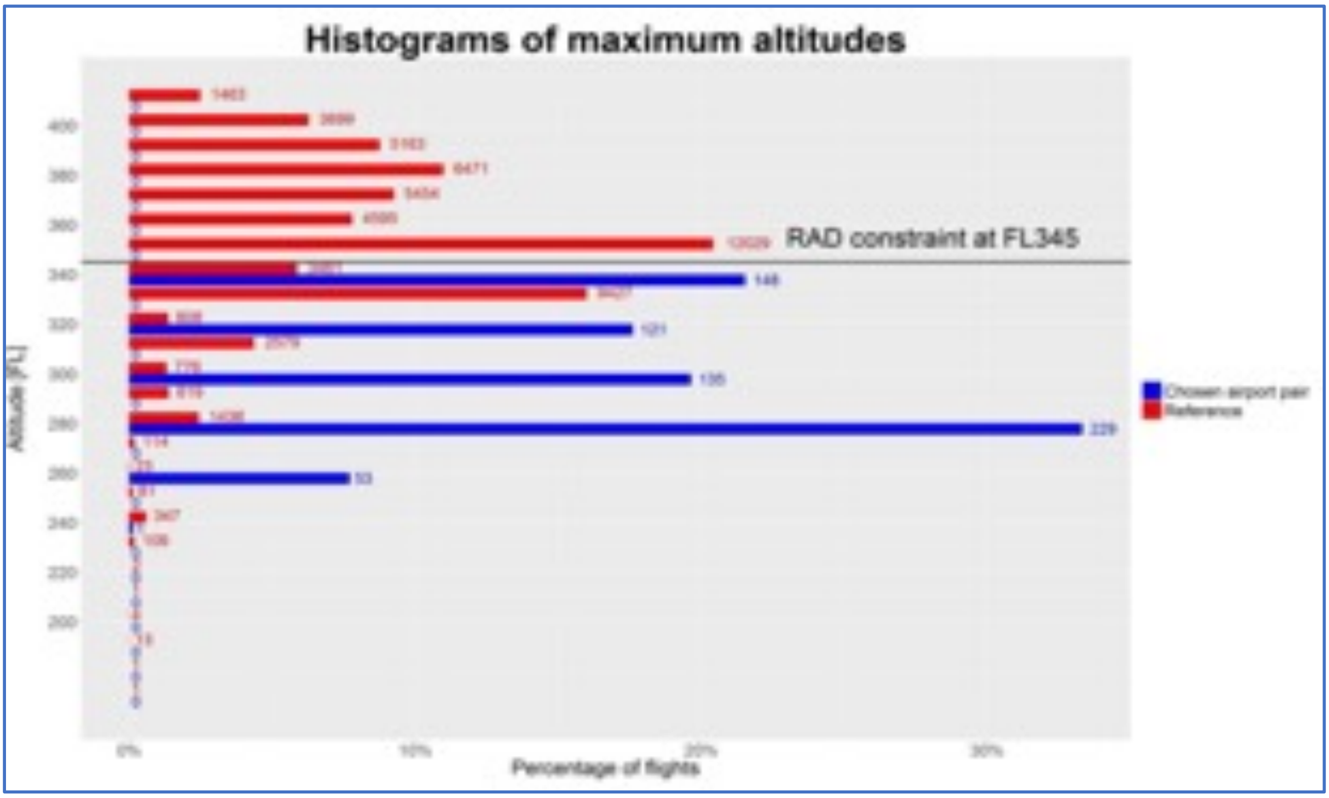

Figure 2: Vertical assessment by PRU (PRU Source)

The reasons for these horizontal and vertical inefficiencies

Priorities of the former world: No delay and cheap tickets

Up to now, after having ensured the highest possible safety, NM, ANSPs, and AOs have made much more effort to minimize the impact of delays, rather than environmentally optimising flight trajectories. From a communication perspective, the aim of zero delay always prevailed over the saving of a few kilos of fuel and CO2, additionally passengers will choose multiple legs, transiting via hubs rather than flying direct if ticket prices for these are cheaper.

Following this logic, Network coordination took place for summers 2018 and 2019 (eNM measures) in order to limit European delays, with rerouting proposals and level-capping. Thanks to these measures, millions of minutes of delay were avoided, but at the same time, a significant amount of additional fuel was burned (with their corresponding CO2 emissions).

The safety requirements

Airspace design and network planning utilises constraints in order to provide a high level of safety, especially in high demand and complex airspace. This is why traffic segregation is implemented, enabling climbing and descending traffic to fly without being required to stop their climb or descent several times because of potential conflicts. Connections between upper airspace and TMAs are therefore not designed with straight segments.

The same kind of segregation also takes place in upper airspace. For safety reasons as well as for capacity reasons, flows are geographically separated from ones travelling in the opposite direction. With such a network design, northbound traffic is separated from southbound traffic, and vice versa, but it leads inevitably to an extension of route lengths.

Where traffic demand levels permit, “directs” are issued by controllers to pilots in order to reduce unnecessary track distance as far as possible. However, this introduces unpredictability into the system, meaning forecast demand within a downstream sector becomes less reliable. This can lead to over deliveries, and as a result ANSPs may reduce their declared sector capacities.

Needs of national air defences

Even though access to airspace has to be granted for all users, the necessity and to a certain extent priority of military activity is obvious, and has to be taken as a given.

With the advent of new generations of fighter aircraft and weaponry, military requirements for segregated areas to be increased in size are being made across Europe.

These new areas, either already created or under development, are part of the 278 existing military areas already operated in FABEC airspace. As an example, LFD300A area, located in the South-West of France, has the following extensions of 150NM x 80NM.

Routing around these military areas leads to additional mileage which has a negative impact on the environmental performance indicator values. Some of this impact has been mitigated through the application of FUA procedures and further work in this area is being pursued.

Tactically, when no longer required, these areas are made available to civil traffic. However due to both Operator flight planning systems and lead times, these cannot always be effectively exploited, again leading to unnecessary carriage of fuel or leg distance.

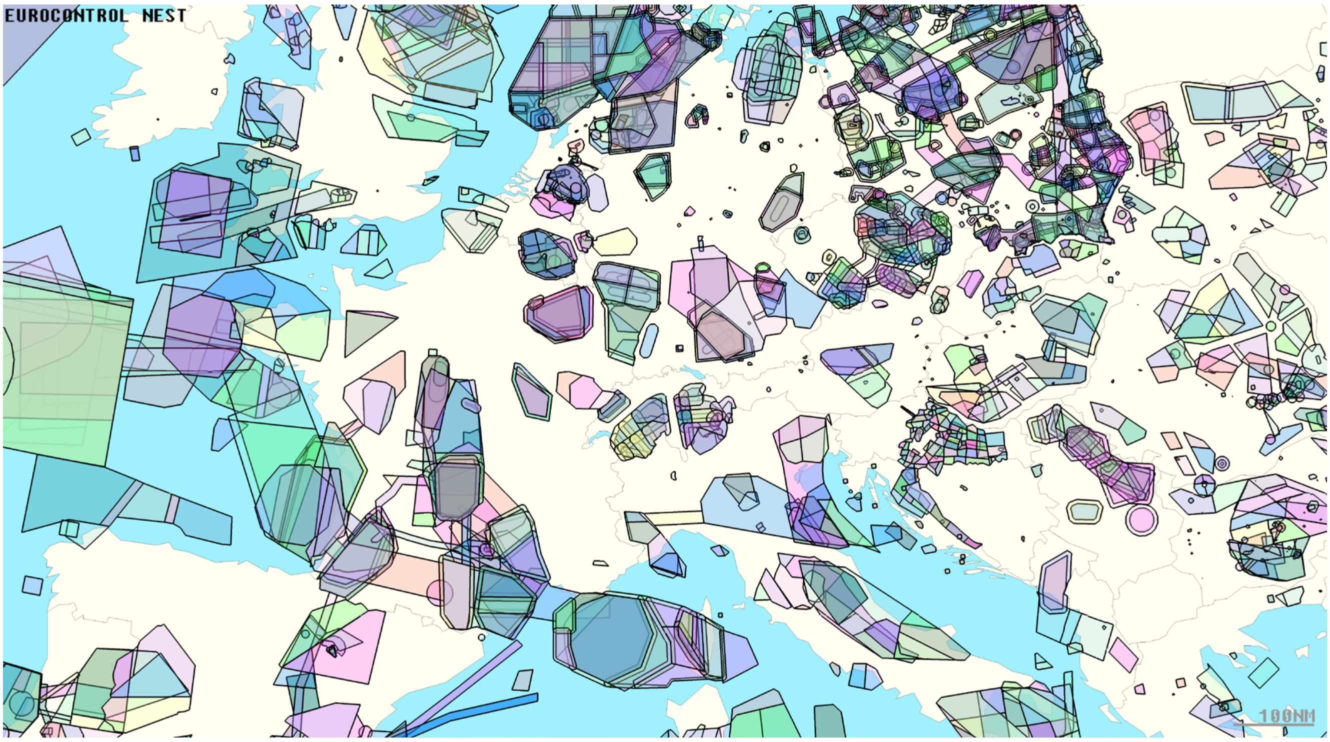

Figure 3: Chart of military areas in FABEC

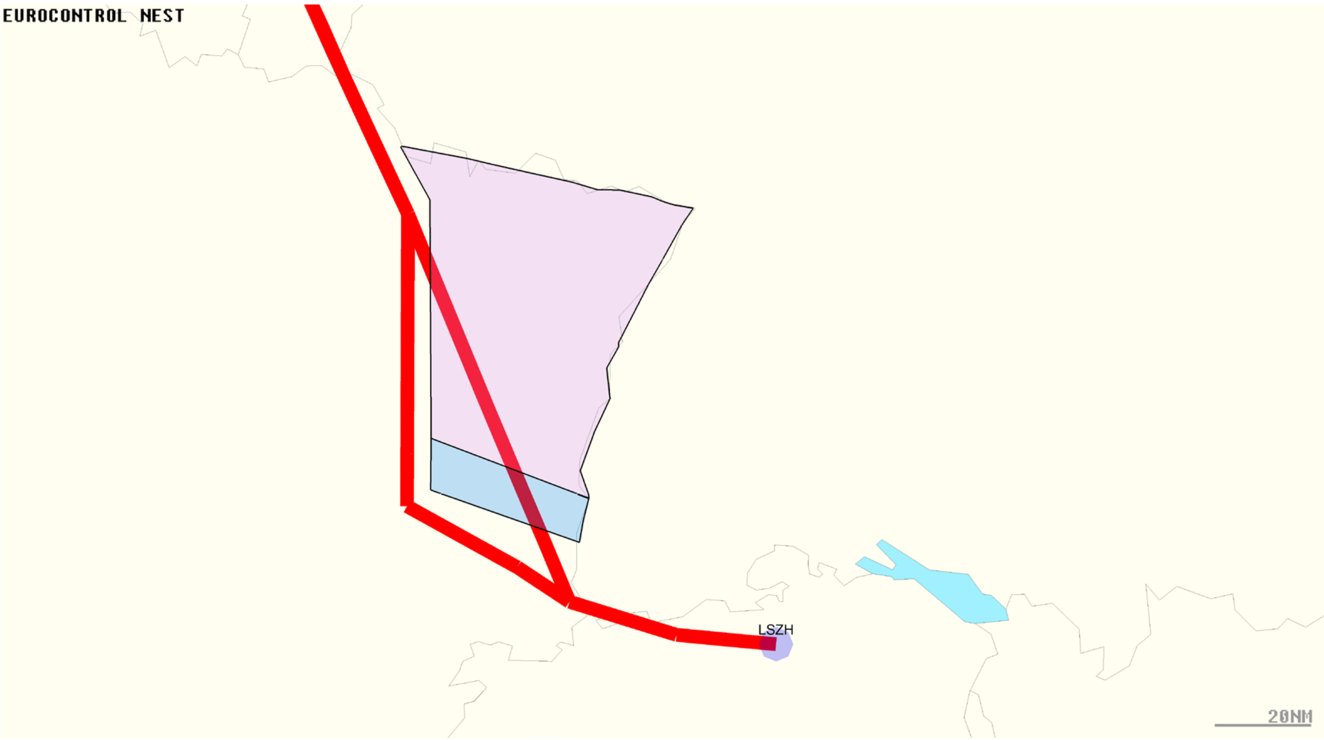

Figure 4: Arrivals LSZH with Mil Act (+12NM)

The choice of the airlines

ANSPs currently provide both a conventional ATS route network as well as a growing Free Route Airspace, offering many possibilities to users to join airport A to airport B. Nevertheless, weather, delays, horizontal or vertical constraints, as well as route charges in different countries, remain as airlines influencing factors in their flight planning and tactical behaviours. Clearly the final flight planning decisions are taken by users, taking account of all the elements fitting to the airline's policy, combining both safety and economic aspects.

The flight planning criteria of an airline can be manifold. Sometimes the preference is filing the cheapest route, sometimes the shortest/fastest one, or sometimes to file a route avoiding adverse weather or an important delay.

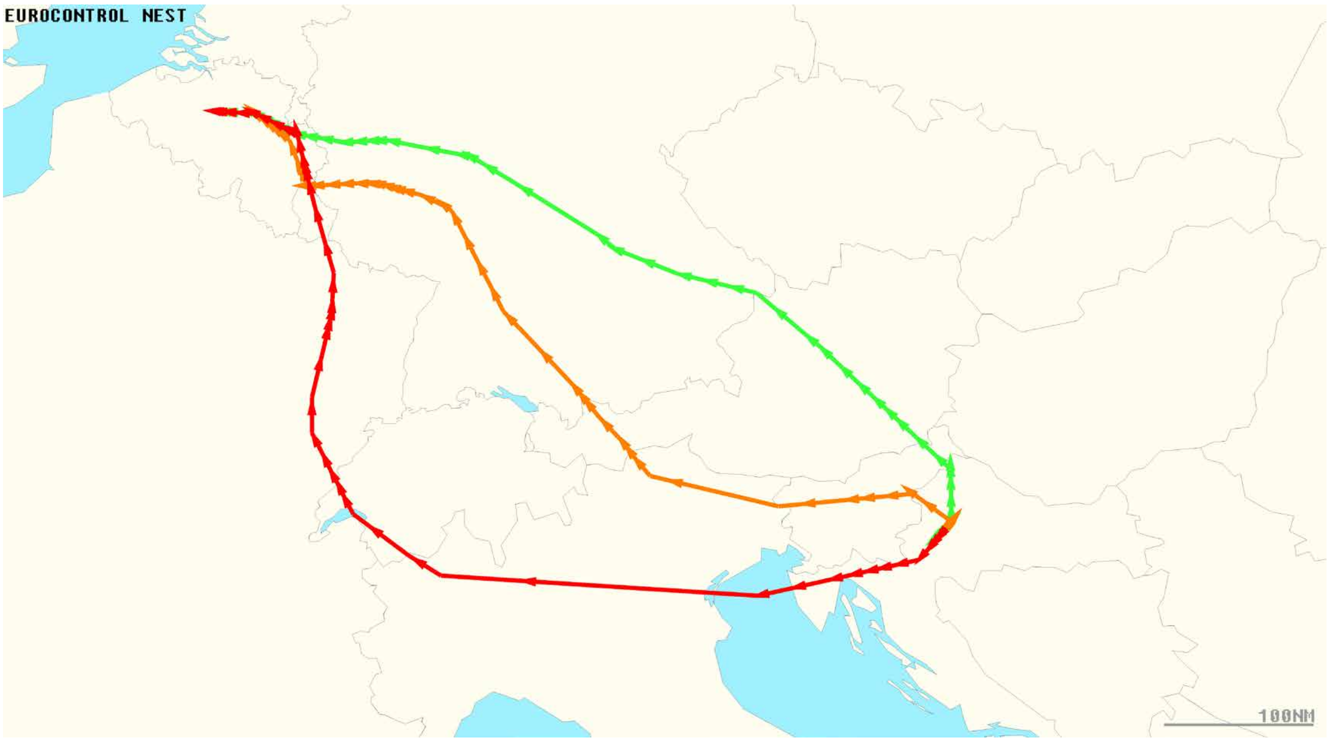

Figure 5: Three Flights Zagreb to Brussels on a summer day

As an example, the figure 5 shows three different flight plans filed for three flights on the same summer day for the identical connection from Zagreb to Brussels.
In the case of a flight plan filed to avoid delay or adverse weather, the role of ATC becomes limited. Directs can of course still be given, but sector distribution must also be taken account of.

Interdependencies

Interdependencies between the different KPAs have a very important impact when pursuing environmental goals. As described in a previous chapter, safety forces ANSPs to implement longer routes to segregate the traffic, leading to additional fuel burn and CO2 emissions.

Interdependency KPA CAPA vs KPA ENV

For more than 20 years, KPA Capacity has had a decisive environmental impact. Due to capacity constraints, strategic measures have been implemented to move traffic flows away from congested and complex sectors. During the pre-tactical (D-1) planning phase, again, where significantly overloaded sectors are identified, rerouting options were employed to mitigate the situation. This developing situation will then be monitored tactically and where necessary additional measures would be used such as regulations or STAM (Short Term ATFM Measures). What is interesting to observe is the way controllers react and its effect on flight trajectories.

The more traffic a controller has, the more difficult it is to environmentally optimize trajectories. As a consequence, directs are still given in peak periods, but much less compared to low traffic ones. Having traffic on direct courses in multiple directions requires more coordination, and this is why controllers tend to stick to published procedures and filed trajectories during peak hours.

This principle is illustrated in figure 6, which shows that KEA values decrease as soon as traffic volume increases. The relationship between traffic volume and additional fuel burn or CO2 emissions becomes obvious.

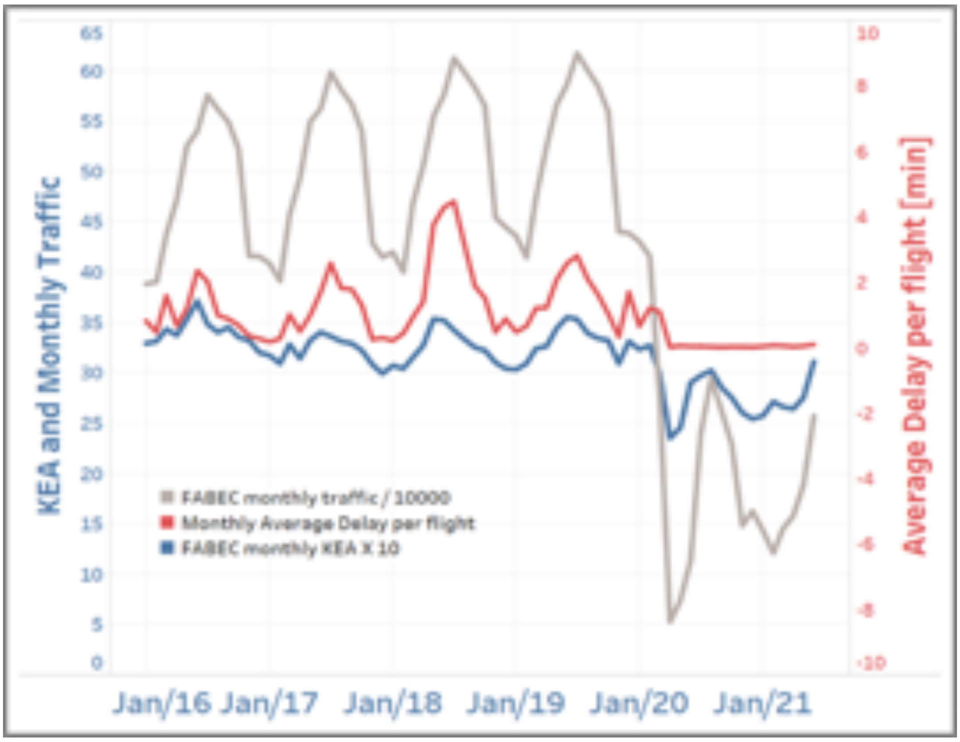

Figure 6: Correlation between traffic, delays, and KEA

Improvements over the last decade in improving the environmental impact of ATC

In recent years ANSPs have expended a lot of effort in an attempt to improve flight trajectories through their working methods and associated procedures. Here are a few examples.

System development

All ANSPs are continually updating and modernizing their technical systems, to a greater or lesser extent. Recent new generations of FDPS, radar screens and associated HMIs have enabled controller working positions to increase sector capacities and have therefore helped ATC to cope with the constantly increasing traffic. Because of these technical evolutions, less restrictions have been implemented than would otherwise have been required and consequently led to important fuel and CO2 savings. According to ANSPs' systems, improvements can vary, but ATC could reasonably offer 15% to 30% more capacity.

XMAN

Additional mileage in lower airspace leads to comparatively higher fuel consumption and CO2 emissions than at higher altitudes. It is therefore of the utmost importance to limit vectoring or holding patterns below FL100.

XMAN (Extended AMAN) has been developed in some FABEC ACCs, to reduce unnecessary additional and reduce the associated environmental footprint of traffic routing to the largest airports within FABEC and to airports just beyond its borders.

The principle is to propose speed reductions in upper airspace with a horizon of more than 200NM prior to reaching the destination in order to facilitate sequencing in TMAs by limiting time spent in vectoring and holding patterns.

Each ACC involved in the XMAN project is responsible for providing XMAN measures for two or three airports.

Figure 7: XMAN projects in FABEC airspace

Free Route

Many efforts have been made in the last 10 years to realise the concept of Free Route Airspace (FRA), and it is still under development with a few ANSPs. Several performance reports have highlighted actual or potential benefits of FRA, this is due to the increased number of connections and way points enabling airspace users to file and fly on trajectories more closely aligned to their optimum.

Performance indicators show improvements. However, it should be noted that cross-border FRA is an area that could be developed further. Inefficiencies at interfaces can still be improved outside the FABEC region, as shown in figure 8, with an illustration of internal and interface inefficiencies. As an example, the internal inefficiency of flown trajectories (KEA) was only at 1.46% in August 2021. Free Route Airspace will continue to bring very important benefits in the future, particularly once technical developments are implemented allowing the reduction of restrictions and constraints still existing in FRA airspaces.

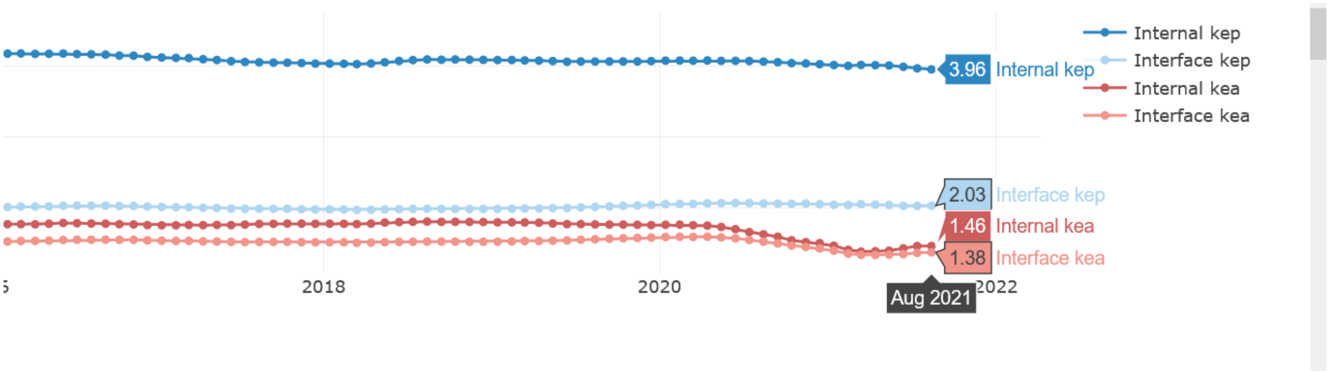

Figure 8: Internal and interface inefficiency in FABEC airspace

CDO/CCO

Continuous Descent/Climb Operations are widely implemented at airports within the FABEC area (see Figure 9). They are aircraft flying techniques, facilitated by ANSPs where all parties must work together collaboratively, across all phases of flight to realise the potential benefits.

The aim of continuous climb or decent procedures are to minimise the time an aircraft is in level flight. These periods of level flight often result in increased fuel burn, emissions and noise compared to a continuous climb/descent. In complex airspaces (like FABEC), it is a challenge to eliminate the level segments, primarily due to safety and capacity reasons.

Figure 9: CDO/CCO in FABEC airports

It should be noted that, due to the nature of operations, CCO suffers much less from inefficiencies when compared with CDO: in 2020, the share of CDO (from Top of Descent) and CCO (up to Top of Climb) was 19.9% and 76.0% respectively. As from the start of the Covid crisis, primarily CDO performance across the FABEC area substantially improved. Due to the reduced traffic demand, there was – literally – more room to facilitate and fly CDOs. This can also be observed from Figure 10.

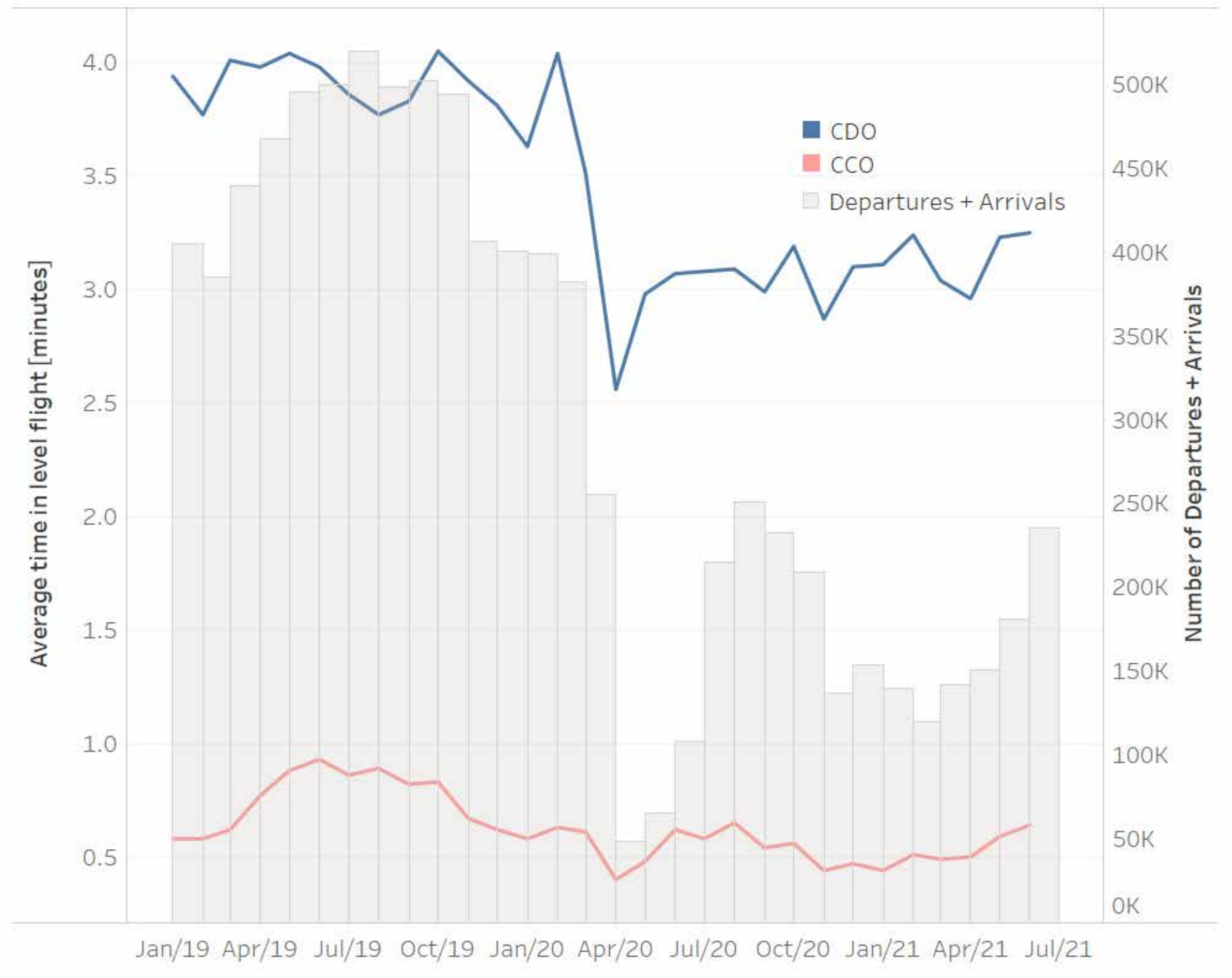

Figure 10: CDO/CCO performance (Data source: https://ansperformance.eu/).

Which operational solutions should be considered and could be developed to limit the impact on climate change?

Trajectories can be improved horizontally, vertically, or both. Nevertheless, a new balance must be found to reduce fuel consumption, reduce exhaust emissions, without negatively affecting capacity. Here are some possible solutions

Limiting the impact of interdependencies

Interdependencies between ENV and other KPAs are very often detrimental to the environment, in particular those related to ATFM. Environmental indicators are supposed to highlight the performance of States/ANSPs/ACCs, encouraging them to find increasingly greener solutions to accommodate the growing number of trajectories. However, current ANSP environment performance indicators assess traffic performance using a network, instead of assessing network performance itself. Moreover, current assessments are made which includes traffic choosing its routes according to weather conditions, military activity or Unit Rates, which are not directly under the control of ANSPs.

Given the situation, ANSPs cannot improve something that is not identified or measured correctly. It is time to require indicators that measure performance metrics which are exclusively within ANSPs' area of competence.

Contrails

With two-thirds of aviation's impact on climate change estimated to come from non-CO2 emissions, contrail avoidance has a key role to play. Condensation trails – so-called contrails – are formed by water, soot and cool air. When water vapour is ejected from the exhaust nozzle of an aircraft engine into sufficiently cold air, it condenses and freezes around soot and other particles in the air, creating tiny ice crystals.

In certain atmospheric conditions, these ice crystals create layers of cirrus clouds, causing a "blanket" effect which keeps warmer air trapped in the lower atmosphere. At night, this has a warming effect on the atmosphere. By avoiding ice-supersaturated regions (ISSRs) in the atmosphere, aircraft can reduce the likelihood of forming these persistent contrails.

Among the numerous ANSPs engaging in contrail prevention research as the future climate protection concept in aviation, Maastricht UAC is presently conducting live contrail prevention trials with DLR, the German Aerospace Centre. This contrail prevention trial is the first of its kind in the world, and will investigate the operational feasibility of contrail prevention by ATC and measure its impact.

The trial assesses how to avoid warming persistent contrails with eco-efficient flight trajectories in live operations. MUAC is examining relatively minor operational measures such as small flight level changes, for example diverting aircraft not more than 2,000 feet up or down from their normal flight path, to reduce persistent contrail formation and contrail cirrus. This requires creating a contrail prevention system, implementing operational procedures for contrail prevention, and the validation of the methodology with satellite image analysis by the project partner DLR.

The findings of these trials will help to fight climate change in a very practical way, demonstrating whether the current meteorological forecast of ISSRs is precise enough in terms of predictability of size, position and time of existence/activity and will show the difficulties in organising the ATM procedures for contrail avoidance. Only a very small proportion of flights is affected by contrail prevention clearances. Optimised air traffic management keeps deviations from the requested flight levels to a minimum and strives for environmentally optimised profiles. There is no horizontal re-routing as part of the trial, and flights in their climb or descent phase within MUAC airspace will in general not be affected.

Inefficiencies at interfaces

All FABEC ANSPs have airspace improvement plans in place, upgrading both their remaining fixed network as well as the new FRA environment. All these airspace improvements have found solutions to shorten trajectories, leading to promising results. Nevertheless, environmental indicators still show inefficiencies. Looking at these metrics in more detail, it shows that inefficiencies at interfaces appear to be one of the remaining sources of inefficiency.

Environmental indicators have recently shown a good performance in HFE, but some city-pairs or traffic flows are still penalized by inefficiencies at interfaces. Bilateral solutions and improvements will have to be found between all stakeholders.

Dynamic RAD

In the Post-Covid period where there is roughly 30% less traffic overall when compared to 2019, peak hours regularly occur. This is why many restrictions which had been relaxed during 2020 are being reintroduced in 2021. The impact of this is that unless they are very targeted, restrictions will always be applied even during periods of low traffic.

Dynamic RAD is a promising project initiated by FABEC, where flexibility is offered to users, by activating restrictions dynamically only when necessary, during forecast periods of high demand, and leaving the majority of the day of operations restriction free.

PBN development

PBN (Performance Based Navigation) procedures enable a very high accuracy in aircraft navigation. The advantage of such procedures is that they can answer to communities' requirement on noise, but they also can provide shorter and more tailored trajectories. Separation between trajectories can be reduced with a higher level of safety, which can be translated into fuel and CO2 savings.

Conclusion

In a rapidly-changing world, air traffic control will continue to have an impact on the environment, and therefore climate change. Whether via the extension of routes in the horizontal dimension, or vertical constraints imposed on traffic. Civil air traffic control is clearly not solely responsible for the inefficiencies which result in the unnecessary release of greenhouse gasses into the atmosphere. Military and civil airspace user choices, also have a major impact on the environment.

- This is why new indicators are needed in order to better understand and improve the situation, (with particular regard to interdependencies).
- Better cooperation between stakeholders is needed, to have a common view and a better mutual understanding.
- A new and commonly agreed trade-off has to be defined between ENV, CAPA, and CEF, followed by a concept how to balance those KPA needs.

Over the last ten years, major programmes such as Free Route, XMAN and the development of CCO/CDO have led to substantial savings in fuel and therefore CO2. Other areas of improvement have already been identified ensuring ATC takes its leading role for continuously reducing its increasingly small negative impact on climate change in the future.

Session 4

Holistic view on policy options

Economic estimates of the climate costs of the aviation sector due to air management: insights for 2018 and 2019

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Abstract

Air navigation service providers ensure that aircraft keep safely apart by prescribing vertical and horizontal distances to each other. In the European Union and its associated members, regulation is carried out via a performance scheme which measures and sets targets for the different key performance areas. For the environmental area, targets were set by assuming that there would be continuous improvements for the Key performance Environment indicator based on Actual trajectory. However, although a higher horizontal flight efficiency (HFE) measurement usually means a more direct flight trajectory, this does not necessarily translate into a climate optimal trajectory. Thus, vertical flight efficiency also needs to be considered. There is also an interdependency between airspace and Air Traffic Management (ATM) Capacity and Environment: when the offered capacity falls short of the demand for flights, ground delays, holdings and traffic shifts to adjacent areas occur. This entails detours and a deterioration of the HFE-indicator.

If we take the short to medium run up to 2030, the estimated EUR CO2 costs will amount to 112 million EUR (1,062,044 tons of CO2 times 105 EUR). In the long run, from 2040 to 2060, the costs would amount to 301 Million EUR (1,062,044 tons of CO2 times 283 EUR). Therefore, a shortfall of capacity leads to delay costs and considerable environmental costs. As capacity is planned in the medium to long-term, traffic forecasts are a crucial element. This means that further research is warranted into the interdependency of traffic forecasts, capacity and environmental costs.

Full paper

The full paper has been published in a journal and can be accessed here:

https://www.revistadyna.com/search/insights-on-the-economic-estimates-of-the-climate-costs-of-the-aviation-sector-due-to-air-management

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An urgent need for a paradigm shift in policy making: ensuring sustainability and disaster mitigation in transport policies

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Abstract

Within the context of the European Green Deal and the imperative to significantly reduce the negative environmental externalities of transport modes, the issue of sustainability in aviation is more important than ever. This paper intends to examine policy options leading to a more environmentally acceptable performance of the sector. The authors suggest that this task is exceedingly difficult. The main reasons for this are inconsistent policy objectives, the lack of a fact base for developing relevant policies combined with techno-optimism and simplified narratives as well as a lack of a solid value system driving policy choices. At present, the policy of the European Commission on air traffic sustainability may be described as ambiguous. While the EC Sustainable and Smart Mobility Strategy (published at the end of the last year) establishes achievable targets for the long-term, the short-term approach of the Commission is oriented towards the extensive growth of air mobility. Regarding the role of ATM, the authors focus on the relationship between traffic volumes, airspace capacity, technological and operational solutions, as well as potential new approaches to airspace as a scarce resource and as a place where polluting activities take place. The obvious limits of the ETS and CORSIA schemes will be discussed as initiatives focussing on the CO_2 impact of aviation in the light of the growing body of research pointing to the potentially more significant non-CO_2 impact. The authors suggest, that while structural changes would be necessary to ensure the sustainability of the aviation sector and could be best implemented at the EU level, such expectations may not be realistic today. In the short-term, progressive Member States may need to take the initiative in implementing innovative new policies and indeed, in order to give effect to fundamental principles of EU law such as the no harm principle or the polluter pays principle.

Introduction

The alarming pressure of climate change has become a constant theme in the news in the past few years and just recently also in policy-making. All recent studies and evidence show that the window to act is closing in on us more rapidly than previously expected. The most recent publication that echoed the startling tone was the IPCC's (Intergovernmental Panel on Climate Change) sixth assessment report that predicts 1.5 degrees of warming in the next twenty years, even with emission cuts[1]. Such an intense rise in temperatures is expected to cause extreme weather and climate events. We do already see these effects occur more and more often in the form of heatwaves, droughts and floods all over the world. Even the editors of health journals worldwide are publishing a joint editorial calling on world leaders to stop climate change, the greatest threat to public health[2].

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[1] IPCC Climate Change 2021 The physical science basis Summary for Policymakers.

[2] British Medical Journal 2021; 374: n1734.

Considering all the worrying future scenarios, it is inevitable that sustainability policies are on the agenda and are considered among the top priorities for lawmakers. There are some promising developments in addressing the issue, mostly in Europe, with the Green Deal setting the ambitious target of becoming climate neutral by 2050, and the Commission recently publishing the Sustainable and Smart Mobility Strategy and the Fit for 55 package of proposals. Both are steps in the right direction, as dealing with climate change does not seem possible without strong government action and legislation. It is, however important that all the policies are fact based, realistic and enforceable, and not only serve as an opportunity to appear progressive and provide superficial temporary fixes. The authors of this paper believe that it is time now for government action as the situation seems grimmer than ever. In this article, we examine whether EU policies and regulations appropriately address and ensure the sustainability challenges of the European mobility sector and aviation in particular. If not, what are its shortcomings and through what policies, political, legislative, regulatory and implementation approaches could the situation be improved.

Setting the scene

Climate change is defined as a long-term change in the average weather patterns that have come to define the Earth's local, regional and global climates[3]. The climate dilemma's presence in the science and policy discussion is not new, it has been on the table for many decades now, with the earliest mentions dating back to the beginning of the 20th century. However, it took until the end of the century to put the first bricks into the wall of the climate change regime. The watershed moment was probably the signing of the Kyoto Protocol (1997), the first robust international environmental agreement, setting legally binding emission reduction targets. After the promise of Kyoto, the new millennium did not bring the expected results, and the commitments were not sufficient to adequately mitigate the effects. The Paris Accord climate policy framework was signed in 2015 by 196 countries, and aims to keep global warming below 2 degrees. Although it does not explicitly refer to aviation emissions – neither international nor domestic, it is widely accepted that aviation is a non-negligible contributor to climate change. The data shows that aviation makes up 12% of global CO_2 transport emissions[4] and is responsible for 2.4% of anthropogenic emissions of CO_2[5].

Aviation contributes to climate change by consuming significant amount of fossil fuels, by burning up these fuels and emitting the combustion products at altitude levels, causing an increase of greenhouse gases in the atmosphere. Another effect is the production of contrails that reduce both the solar radiation reaching the surface and the amount of longwave radiation leaving the surface of the Earth, causing a heating of the troposphere[6]. It is clear that the climate impact of aviation goes well beyond CO_2 emissions. As a recent EASA report found, "aviation emissions are currently warming the climate

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[3] NASA climate.nasa.gov

[4] https://theicct.org/aviation

[5] D.S. Lee et al. (2021), The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmospheric Environment, Volume 244.

[6] D.W. Fahey and Lee, D.S., (2020). Aviation and the Impacts of Climate Change. Aviation and Climate Change: A Scientific Perspective, Carbon & Climate Law Review Volume 10, Issue 2 (2016) pp. 97 – 104.

at approximately three times the rate of that associated with aviation CO_2 emissions alone”[7]. Gössling and Humpe (2020) also emphasized in a recent study that a huge share of aviation’s emissions are not accounted for currently in the Paris Agreement and are not covered by climate policies, as they tend to focus on CO_2 emissions only[8].

Currently, the demand for air travel clearly exceeds existing and potential efficiency gains leading to an overall growth in emissions from the sector[9]. According to ICAO, there is an expectation of continued growth of aviation once the pandemic is over[10]. Such a growth might cause emissions to double or even triple by 2050. West (2018) concluded that if we insist on continuous open-ended growth, not only does the pace of life inevitably quicken, but we must innovate at a faster and faster rate[11]. McManners (2016) stated that “the policy stalemate exists because it is neither understood nor accepted that sustainability requires systemic change”[12]. Barr and Prillwitz (2012) believe there is growing support for sustainability concepts, but there is a large divergence between rhetoric (policy) and reality[13]. Overall, it can be observed in aviation that policy-makers rely heavily on future prospects of technological innovations and developments, also referred to as techno-optimism. According to Pidcock and Yeo (2016), by 2050 carbon emissions from international aviation will still represent 12% of the global CO_2 budget even if technological and operational efficiencies are maximized and the total demand for conventional jet fuel is met with alternatives[14].

Context: aviation in the EU

As McManners (2016) put it: “Currently the question is phrased as: this is aviation as we know it, so how do we mitigate the emissions?”[15] The industry is in a unique position, as its cargo services are indisputably needed for the functioning of the world economy, while at the same time leisure air travel can be seen as an unnecessary luxury society could forego. According to IATA, international passenger traffic climbed 4.1 percentage points in 2019 compared to 2018, while capacity rose 3%.[16] International aviation was responsible for the largest percentage increase in greenhouse gas emissions over 1990 levels (+129 % in 2017).[17] While modern airplanes are more efficient than those in the past – using 24% less fuel in 2019 than in 2005, overall emissions in Europe have risen by 16% in the same period because of the 60% increase in passenger kilometers flown.[18] 2020 was supposed to be about handling the so called ‘capacity crisis’ and expanding the infrastructure, while – however contradictory it may sound – trying to mitigate the industry’s impact on the climate. What happened instead was a previously unprecedented decline

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[10] ICAO Safety Report, 2020.

[11] Geoffrey West: Scale; Weidenfeld & Nicolson, Great Britain 2018, p. 31-32.

[12] McManners, Peter (2016). Developing policy integrating sustainability: A case study into aviation. Environ-mental Science & Policy. 57. 86-92.

[13] Stewart Barr and Jan Prillwitz (2012) “Lead has become carbon dioxide”: framing sustainable travel in an age of climate change, Local Environment, 17:4, 425-440.

[14] Pidcock, Roz, Yeo, Sophie, (2016). Analysis: aviation could consume a quarter of 1.5C carbon budget by 2050.

[15] McManners, Peter (2016). Developing policy integrating sustainability: A case study into aviation. Environ-mental Science & Policy. 57. 86-92.

[16] https://www.iata.org/en/pressroom/pr/2020-02-06-01/

[17] Greenhouse gas emissions from transport in Europe – European Environment Agency (europa.eu).

[18] EASA Aviation Environmental Report, 2019.

of air traffic as a consequence of the Covid-19 pandemic. Countries went under strict lockdowns and tourism stopped almost entirely. In the spring of 2020, European air traffic was down 80% on average compared to the year before[19].

The forced pause could have been the perfect opportunity to introduce structural change through novel policies and regulations; to „build back better", and start anew as an industry that is taking the climate pledges seriously. In Europe, the European Commission is dedicated to be carbon neutral by 2050, and to achieve a 55% reduction of greenhouse gas emissions by 2030[20]. The transport sector in the European Union is responsible for 25% of greenhouse gas emissions, which needs to be cut at least 90% for a shot in reaching the climate goals.[21] For these goals to be realistic, it would be necessary to urgently instigate fundamental changes, backed by fact-based policies in the entire economy, including aviation.

The Sustainable and Smart Mobility Strategy EU initiative, published in December 2020 reads as a promising concept on how to act on the Green Deal goals, listing improving multi¬modality and pricing carbon as important aspects. The recent scheme named "Fit for 55" is a huge step forward bringing the 2050 net zero goal into a more realistic timeframe and balancing the burdens of achieving this aim between the present and the future generations. The major aviation related components of the EU plan are the introduction of an EU-wide minimum tax rate for aviation fuels, a compulsory minimum rate of sustainable aviation fuels, and a revamp of the European Emission Trading Scheme. The measures are interlocked as economic and regulatory side of the same aim: to strengthen the polluter pays principle – a basic EU principle set out in the Treaty on the Functioning of the European Union. The end-product of these proposals is yet to be seen; however they should definitely be recognized as a forward-looking attempt in enforcing the polluter pays principle.

Where ATM and ANSPs can play an important role is optimizing their operations – meaning providing clear forecasts and uninterrupted service to airspace users to fly the most efficient routes possible – a practice that is ideally already in place. ANSPs have invested a lot to enhance the airspace capacity and reduce delays. As an example, horizontal flight efficiency is already over 96% due to the flexible use of airspace and the new Free Route environment.[22] It is important to underline that the remaining proportion cannot be eliminated due to unforeseeable circumstances, such as weather conditions or airspace restrictions. In any case, the ATM sector will not resolve the sustainability problem of the aviation sector. The focus should be on aircraft technology and keeping both CO_2 and non-CO_2 impact at an optimal level.

Current direction – a critical approach

This paper looks at the ATM industry as part of the aviation sector which is on turn only one segment of transport and mobility. Although it is important that each of the concerned parties do all within their

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[19] Daily Traffic Variation - States (eurocontrol.int).

[20] The European Green Deal, 2019

[21] Ibid.

[22] Environmental Assessment: European ATM Network Fuel Inefficiency Study (2020)

reach to be sustainable, climate change is unique in the sense that it is a complex problem overarching different sectors. Addressing this problem requires a holistic and pragmatic approach. There is a clear need for stronger, immediate state intervention. It is a state responsibility to ensure public goods. Markets do not usually supply those, since market actors have a different objective, which is profit. While we need to acknowledge that climate change is a global problem that needs to be addressed globally, we consider that the EU has a political, legal and moral obligation to act.

The authors find that the most important concerns with the current aviation sustainability policies are the following. First, the lack of fact-based policies resulting from ignoring the non-CO_2 effects of aviation and embracing techno-optimism in policy-making. Second, the existence of competing policies. Mobility and the internal market are still priorities when policies such as maximizing airspace capacity and promoting cheap mobility are imple¬mented. While there is a clear expectation to reduce emissions, the possibility of introducing environmental thresholds is not even considered. Third, the lack of clear responsibilities for achieving sustainability objectives through executing climate related policies and enforcing rules. The polluter pays principle and the precautionary principle are often overlooked and the external costs of aviation are still not internalized.

The intentions and communication of the European Union show a commitment and willingness to act but so far short-term economic considerations seem to override environmental concerns. There are no taxes on air travel in most of the member states and the current market based measures are heavily criticized as ineffective and as a distraction from the real solutions. They require significant input of energy, human resource and money that could be better invested in introducing structural changes as well as in developing break¬through technologies that can bring meaningful change and have a lasting impact. The current state of affairs may further delay investments and regulatory action that could actually lead to a decrease in emissions. In the case of current market based measures, such as the EU ETS and CORSIA, moral and practical questions both arise. A moral question arising is of fees versus fines. Putting a price on carbon, in the words of Michael Sandel, removes the moral stigma that is properly associated with it, by turning pollution into a commodity. It basically gives companies a moral license to pollute.[23] The most important technical weakness is that neither CORSIA nor ETS cover the non-CO_2 emissions of aviation. Non-CO_2 emissions in aviation have been neglected, however a growing body of scientific evidence suggest that the non-CO_2 impact might be more harmful to the environment than CO_2 emissions and may cast a different light on SAFs. ETS has a relatively small scope, covering only intra-EU flights. The scheme provides a significant number of free allowances for each sector every year, with aviation receiving 82% of its carbon credits for free in 2019.[24] CORSIA, despite covering a geographically larger territory than ETS, is still less ambitious, as there is no emission reduction included. While the ETS operates with decreasing the cap on emissions every year, CORSIA is aiming for no net emissions after 2020. CORSIA, as an ICAO initiative is not binding for Member States. Offsets as a whole cannot be fully trusted in delivering the planned reduction of CO_2, as there are many inconsis-

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[23] https://www.nytimes.com/1997/12/15/opinion/it-s-immoral-to-buy-the-right-to-pollute.html
[24] https://ec.europa.eu/clima/policies/ets_en

tencies within offsetting projects which are also widely criticized on different grounds including greenwashing and the general inefficiency of offsetting projects. Trading emissions in a carbon market and offsetting hold political and financial advantages, but little for real environmental change. It makes sense for politicians to prefer these initiatives instead of harsher, likely less popular interventions, which may also entail drastic state intervention in the traditional operation of markets.

Optimal scenarios

The starting point for building a new policy framework should be to clearly define the goals and prioritize these goals compared to other interconnected or even competing policy objectives. In case of Europe, the ultimate goal is climate neutrality, where the transportation sector including aviation has a lot to contribute in the years ahead. It is of high importance to have an answer when circumstances jeopardize or eliminate the ideal scenario and policy makers need to make a choice between for example environmental goals and economic growth targets. If these value choices are not clarified at the very beginning, it will cause confusion and reduce social acceptance. Once the goals and the priorities are set, decision makers need to assess the available policy and regulatory tools, their potential effects and the interdependences in the future framework.

As in most industries, the economic benefits of aviation are delivered by profit driven private-law entities, and among others, one of their main goals is to deliver financial value for their shareholders. While most aviation stakeholders have started paying gradually more attention to environmental aspects, these could only be considered as a secondary priority in most competitive business environments and should be interpreted in the context of competitive markets and the motive for maximizing profit. It seems easy to concede, that we cannot expect business entities to solve social, or ecological issues at scale, without the appropriate incentives, or disincentives in place. If climate change is really considered an existential threat – as it currently is by scientific consensus – it should be the duty of national governments and in a European context the EU to ensure, that the most important sustainability goals take precedent over other policy ambitions. To do this, they would need to make sure that “sustainability ethics” prevail in all existing and future policy frameworks and regulations, possibly meaning giving up shorter term economic benefits for longer term sustainable economic results. Also, it is key to realize, that welfare to society should no longer mean economic prosperity in the first place, but social welfare in a wider context, where we move away from anthropocentric regulations, considering the human as a part of the global environment as opposed to a consumer.[25]

Any and all policies need to be fact based or they will lose their validity. Aviation and ATM policies need to be based on a clear understanding of the non-CO_2 impact of aviation. With the appearance of ‘wicked problems’, the approach to policy-making should also be holistic, interdisciplinary and intersectoral. When we aim to make aviation greener, we cannot overlook the interconnections with the wider context of transportation, mobility, agriculture, energy and other sectors. The deep understanding of all

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[25] Jan G. Laitos and Lauren Joseph Wolongevicz, Why Environmental Laws Fail, 39 Wm. & Mary Envtl. L. & Pol‘y Rev. 1 (2014), https://scholarship.law.wm.edu/wmelpr/vol39/iss1/2

related sectors and the knowledge of the options available and their long term effects in subjects like multimodality, alternative fuels, new technologies, incentive schemes, etc. must ensure, that we do not transfer negative externalities from one sector to another but reach an overall decrease of those across an extended transportation value chain. The above would also mean, that conflicting policy objectives should be addressed, and priorities in legislation should be aligned.

As of today, there is still a considerable amount of missing information. This means that we cannot make sure that social or economic convenience would not override scientific reality[26]. Looking at just some of the examples shows that there is a considerable amount of research to be done in the field of aviation alone to be able to make informed decisions on policy-making and regulation. First, it must be defined what activities produce pollution and what their effects are to the environment.[27] While we have a strong understanding about the amount of CO_2 emissions in aviation, we know considerably less about the amount and impact of non-CO_2 effects like water vapour, NOX, CO and SOX. Looking at ATM specifically, the initial version of the SES 2+ legislative package had proposals for the introduction of a single unit rate and the modulation of route charges in the EU, both with the expected result of better environmental performance. While these initiatives may sound promising, there was in fact no impact assessment to support these proposals, to give the stakeholders an idea about the expected results, or to address the various questions and concerns, the concept of these changes raised.

Part of the long term solution could be, that the environmental "costs" would be paid by the polluters, according to the polluter pays principle, which would inevitably lead to higher air fares. Acknowledging the drawbacks of a price increase in flight tickets, looking at the cost of flights in a wider context would probably create a better balance between the value of air travel and its actual total cost.

Ambient pollution requirements and air quality standards – Making the Member States responsible for keeping the volume of pollutants emitted by the actors of the aviation sector below the emission targets set in European directives, by their local policy mix. It also provides a level of flexibility for the polluters, as they can decide how to meet the criteria set by the regulation. Clear, gradually increasing emission thresholds and efficient measures for non-compliance. Mandatory thresholds and penalties, limiting airspace capacity.[28]

Revising the quotas/emission schemes – To ensure an effective system, we need gradually decreasing, non-transferable quotas in place to put pressure on the industry to innovate in order to accelerate a technological paradigm shift and to explore alternative ways to operate aviation in the context of a wider transportation market.

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[26] Ibid.

[27] Efthymiou M. The fundamentals of environmental regulation of aviation: a focus on EU emissions trading scheme. Aeron Aero Open Access J. 2021;5(1):9–16. DOI: 10.15406/aaoaj.2021.05.00122

[28] Taylor CM, Pollard SJ, Angus AJ, Rocks SA. Better by design: rethinking interventions for better environmental regulation. Sci Total Environ. 2013 Mar 1;447:488-99. doi: 10.1016/j.scitotenv.2012.12.073. Epub 2013 Feb 12. PMID: 23410870.

Technology, Infrastructure and process control – As a starting point, the limits of the existing technological potential should be clarified, to understand what could be achieved, with the solutions already available. Technological solutions in the development phase also need to be considered. On the other hand it must be realized, that the further ahead industrialization is assumed and the larger the impact of yet non-existent technologies is expected to be, the higher the risk of failing to reach policy objectives. In other words, policies cannot be based on dreams and over-optimistic expectations.

Economic instruments could be taxes of a wide variety imposed on plane tickets, flights distance covered, taking into account environmental performance, operational performance, load factors, the time of airspace use and many other aspects and characteristics of aviation. Besides taxes, incentivizing not polluting, or more climate friendly behaviour is important, together with ensuring that the preferential treatment for environmental performance reflects the importance of the policy goal and acknowledges related investments. Information based instruments could include data of the environmental performance of businesses made publicly available to incentivise better environmental behaviour through potential impact on corporate reputation.[29] This data could be collected, monitored and published for example by EUROCONTROL or the Network Manager. A pan-European environmental impact transport data-base could also be developed in order to facilitate the identification of the optimal transport mode for a given destination. Intermodality should be encouraged and driven by sustainability objectives. Environmental stakeholders should be involved in EUROCONTROL and NM governance mechanisms.

Registration, labelling and certification could make customer choices even more simple, as environmental performance could be assessed simply and quickly by the end users of the services.

Conclusion

In this paper, the authors have attempted to examine if EU policies and regulations appropriately address and ensure the sustainability challenges of the European mobility sector and aviation in particular. If not, what are its shortcomings (e.g. in respect of the factual basis, consistency, role of state v markets, public value creation, etc. in particular) and through what policies, political, legislative, regulatory and implementation approaches could the situation be improved? As the article highlights, there are currently some promising initiatives, however those are not yet proportionate to the severe climate change situation. There is an urgent need for fact-based, harmonised policies with clear objectives and clear responsibilities for implementing them. On the European level, the best suited actor to deliver them is the European Union. There seems to be undeniable willingness, but techno optimism and prioritization of short term economic and mobility objectives still seem to prevail. Therefore, the difficult part is still ahead and concrete steps are needed. State actors (including the EU) need to acknowledge that structural changes will not be driven by market actors whose main responsibility is creating profit, not public goods. There is a need for urgent and meaningful state intervention, however difficult this may be. It is in our collective interest – including the aviation industry – to reinvent our present for the sake of our future.

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[29] Ibid.

A holistic approach towards flight efficiency: maximising social welfare

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Abstract

In February 2021 the European aviation sector published Destination 2050 – its roadmap towards achieving net-zero emissions by 2050. The roadmap proposes a pathway of improvements along 4 pillars: (i) technology, (ii) ATM and operations, (iii) sustainable aviation fuels (SAF) and (iv) economic measures, all having a crucial role in reducing emissions from aviation.

This paper elaborates on the role of aircraft operations and ATM in achieving the climate goals. Furthering the analyses presented in Destination 2050, we propose a more holistic view on tackling network inefficiency, highlighting the importance and potential of a sector-wide collaborative approach. Interdependencies between various factors – including CO_2 and non-CO_2 emissions, costs, local air quality, noise and safety – complicate the definition of accurate metrics to assess the contribution of ATM in CO_2 emissions.

The paper identifies challenges related to the current measurement framework, which emphasises ATM-efficiency using time- and distance-based metrics, and highlights benefits of a more holistic approach. This framework makes a trade-off between the (social) costs and benefits of implementing ATM-related measures to reduce emissions. By identifying how various measures affect different stakeholders, including passengers, airlines, ANSPs, as well as the broader impacts on society, policies and actions can be identified to achieve outcomes that maximise social welfare.

Introduction

International aviation plays an important role in modern society. Pre-COVID, air travel was however also responsible for 2 to 3% of global anthropogenic CO_2 emissions (Cames et al., 2015; Pidcock & Yeo, 2016; Becken & Pant, 2020). Considering non-CO_2-effects, aviation's contribution to man-made climate change is even estimated two to three times as large (Lee et al., 2009, 2020; Grewe et al., 2017; Grewe, 2019; Lee, 2018; EASA, 2020; Lee et al., 2020). It is expected that these numbers will rise substantially if aviation does not alter its (emissions) course, especially when other sectors decarbonise more rapidly (Cames et al., 2015; Pidcock & Yeo, 2016; Becken & Pant, 2020).

Committed to play a part to the required sustainability transition and keep fulfilling their societal role, European airlines, airports, air navigation service providers and aerospace manufacturers committed to realizing net-zero CO2 emissions by 2050 on all flights departing the European Union, the United Kingdom and the European Free Trade Association (EFTA) (Destination 2050, 2021). This commitment was based on Destination 2050, which investigated numerous sustainability measures in four pillars:

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improvements in aircraft and engine technology, improvements in air traffic management (ATM) and aircraft operations, the use of sustainable aviation fuels (SAF) and economic measures (NLR & SEO, 2021). Starting from a hypothetical no-action scenario including 1.4% and 2.0% compound annual flight and passenger growth, net-zero CO_2 was found to be achievable by 2050 through a combination of in-sector emissions reductions (92%) and carbon removal (8%). Despite demand impacts due to the cost of sustainability measures, positive growth rates were shown to be maintained.

Improvements in ATM and operations, noted to be especially relevant in the short and medium term, were projected to realise CO_2 reductions by 5% in 2030, increasing to 6% by 2050. Within that pillar, the realisation of ATM-related benefits – as for example delivered by the Single European Sky (SES) and its associated research programme (SESAR) – were anticipated to yield the largest benefits. The report also noted interdependencies and trade-offs between CO_2 emissions and, for example, noise and local air quality impacts around airports. Moreover, the work estimated CO_2 emissions reduction potential beyond what is captured by traditional (ATM-focused) environmental efficiency metrics (based on Vranjkovic & Brain, 2020, and EUROCONTROL, 2020a) and recommended to update current environmental KPIs. Last, it emphasised that in order to capture the decarbonisation potential identified, actors from across industry should work together. Historically, stakeholder positions and actions have not always subscribed to that collaborative approach.

Contributing to making that transition, this paper argues a more holistic approach to optimising airspace and ATM would allow for realising meaningful societal benefits. It makes this point by expanding the analyses presented in Destination 2050, indicating more clearly how different stakeholders – including passengers, airlines, and ANSPs – are expected to gain. Before presenting that assessment framework, the next sections however first describe several relevant (environmental) challenges for ATM and briefly discuss stakeholder priorities. The paper ends with recommendations and conclusions.

Environmental challenges for ATM

As highlighted by Destination 2050, ATM-related improvements are crucial in reducing the environmental and climate impact of aviation. Nevertheless, there are a number of (policy) challenges in that area that need to be addressed.

Performance indicators

The environmental performance indicator as currently applied in the SES framework is horizontal efficiency (European Commission, 2019a), based on last file flight plan (KEP) or actual trajectory (KEA). Horizontal efficiency metrics are distance-based and therefore do not and cannot capture effects such as wind: re-routing to avoid headwinds or benefit from (favourable) tailwinds can help reduce fuel consumption and associated emissions, even though the distance flown increases, and horizontal efficiency decreases.

Interdependencies

Throughout the flight, and especially in the airport vicinity, various quantities of interest are related in an interdependent fashion, requiring trade-offs to be made (Sustainable Aviation, 2017; EUROCONTROL, 2018; BLUE MED et al., 2020). Some examples are listed below:

- a more fuel-efficient route might increase flight distance and time, but make a larger claim on capacity in particular airspace regions;
- a shorter (or: more fuel efficient) departure or arrival route might increasingly expose sensitive communities in the airport vicinity to noise – or, put in reverse: lower noise exposure might increase CO2 and other gaseous emissions and associated environmental impacts (e.g. on local air quality and biodiversity);
- a more fuel-efficient route might have a larger (negative) climate impact taking into account non-CO_2 effects, for example if the route traverses more climate-sensitive areas (Grewe et al., 2017);
- capacity shortages in highly demanded airspace results in congestion and increasing the number of air traffic control operators available might alleviate queues, enable closer flight monitoring and suggestions to reduce environmental impact, but on the other hand increases cost.

Stakeholder priorities

The aforementioned interdependencies generally have cost implications as well. For an aircraft operator, more fuel-efficient routing will reduce fuel and emissions cost, but might increase ATM-related expenses and other operational costs (e.g. crew and maintenance cost). Following local rules and regulations, airport operators and ANSPs typically focus on reducing noise exposure during the first and last phases of flight, bringing health benefits to local communities, but at the same time possibly increasing cost, fuel burn and CO_2-emissions.

Assessment framework for costs and benefits

Considering the challenge of different priorities between stakeholder groups in ATM optimisation, a social cost-benefit analysis (SCBA) framework is a useful tool for identifying the impacts of ATM optimization for different stakeholders. An SCBA is an instrument for consistently charting and weighting all the effects of a policy measure or investment. The effects are broken down by consumers, producers (companies), wider economic impacts and external impacts including effects on climate, noise nuisance and local pollution. Moreover, the SCBA framework allows to include distribution effects of the impacts, distinguishing between local and global impacts. All effects are monetised (i.e. expressed in a monetary value), allowing for a comparison of all the different impacts.

Traditionally, cost-benefit analyses (CBAs) are applied to assess investments, and for appraisals of major projects. The European Commission developed a guide to CBA[1] in 2014 (European Commission, 2014). This guide is used as a basis for decision making on the co-financing of projects over € 50 million under the European Regional Development Fund and the Cohesion Fund. The EC's guide presents general guidelines for conducting CBAs in the transport sector, including a financial assessment on investment

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[1] The terms CBA and SCBA are in this context similar. In this report we use the term SCBA to underline that the cost-benefit framework considers the impacts on the society as a whole. Here we use the term CBA for consistency with the respective reference.

costs and revenue projections, and an economic assessment on impacts on travel time, operating costs, safety, noise, air pollution and climate change.

More recently, SEO (2021) has developed guidelines for conducting SCBAs in the field of aviation in the Netherlands. This study provides further guidance for appraising impacts specifically for the aviation sector, focusing on aviation-specific valuation of travel time, as well as on the assessment of negative external impacts of air transport. Similarly, EUROCONTROL (2020b) collects a set of standard inputs for economic and financial ATM-related analyses and appraisals. In the US, a similar guidance document is provided by the FAA (FAA, 2020).

SCBA in ATM

The SCBA framework is well applicable in the context of ATM. However, relatively few socio-economic impact studies or SCBAs in the field of ATM have been conducted over the last decade. The most recent macro-economic impact assessments or cost-benefit analysis concerning Single European Sky date back to 2011 (SESAR Joint Undertaking, 2011). In the 2017 assessment of Single European Sky by the European Court of Auditors, the European Court of Auditors flagged that “individual R&D projects were launched without the support of a specific cost benefit analysis demonstrating their added value (European Court of Auditors, 2017). In the context of ATM, the SES Performance Scheme (European Commission, 2019a) puts binding performance targets on safety, environment, capacity and cost-efficiency. The performance scheme acknowledges interdependencies over different key performance areas, stressing these should be duly considered.

Although SCBAs are typically conducted to assess policy or investment decisions, such a framework is also applicable to identify how ATM-improvements impact ANSPs, airspace users, passengers and other stakeholders such as local residents in different ways. A comprehensive framework that addresses ATM-related interdependencies and appraises the impacts of different route decisions is a valuable tool to achieve socially optimal outcomes.

Table 1 presents how changes in ATM impact different stakeholders and shows how a more holistic assessment may help to achieve better outcomes than optimizing specific KPIs for individual stakeholders

ANSPs and airlines

Airlines tend to make route decisions based on the total route costs. In determining the most cost-effective route, a trade-off is (amongst others) made between fuel burn costs and ANS charges. Higher charges in strategically well-located areas could currently merit a detour. As such, a shift towards CO2-optimised routing could imply a shift of revenues between ANSPs.

Additionally, ATM improvements could lead to increased travel time reliability. This might reduce (ATM-related) delays, from which airlines may benefit, e.g. through a decrease of lost connections.

Actor	**Impacts**	**Impact in €**
ANSPs	Charges revenues Shift of revenues between ANSPs Investment cost …	+ / – € . . . . .
Airlines	Fuel and CO2 compliance costs ANS costs Other operational cost (e.g. crew, delays, maintenance) Investment costs …	+ / – € . . . . .
Customers (passengers / cargo shippers)	Air fares Travel times …	+ / – € . . . . .
External impacts	Local environmental impacts (e.g. air quality) Global environmental impact (e.g. climate change) Noise Safety ….	+ / – € . . . . .
Total	**Sum of all impacts**	+ / – € . . . . .

Table 1: Overview of costs and benefits in ATM decisions.

Customers (passengers and cargo shippers)

ATM improvements that reduce fuel burn and CO_2 emissions (such as CO_2 optimised routing) impact customers in two ways. Firstly, cost changes – both due to fuel/CO_2 costs and ANS costs – are (at least partially) passed through to the end consumer, leading to higher (or lower) air fares (or cargo shipping costs). Secondly, route choice decisions may lead to longer or shorter travel times. Time savings yield benefits for passengers (and cargo), that can be monetised by means of a 'Value of Travel Time'. Additionally, ATM improvements may increase the reliability of the travel time. This yields benefits for both air transport users, for their planning of travel after the flight, and reduces the risk of missed connections.

External impacts

External impacts of air transport mainly include CO_2 emissions, non-CO_2 emissions such as oxides of nitrogen (NOx) and particulate matter (PM), and noise. The Handbook on the external costs of transport (CE Delft, 2019) provides a comprehensive overview of methodologies and input values that can be used to estimate external costs of air transport. Aviation safety is another external impact that should be considered in an integrated cost-benefit assessment.

When determining the external impacts, it is important to identify where impacts have an effect. Some impacts are local (noise, local air quality), whereas others (most notably climate change) are global impacts. In assessments at national level, local costs and benefits are often weighed more strongly than global issues. Considering the international nature of the aviation industry, cost-benefit decisions should be assessed at the international level.

CO_2 emissions

CO_2 emissions form the core of the (negative) external impacts of aviation on climate change, and are bound to strict targets for 2030 and 2050 – following the Fit for 55 package and the EU Green Deal

(European Commission, 2019b). In an SCBA, CO_2 emissions are monetised through 'climate change avoidance cost', i.e. the incurred costs of mitigating the impacts of CO_2 emissions on climate change.

Non-CO_2 emissions

In addition to CO_2, other emissions, such as oxides of nitrogen (NOx), water vapor (H2O), sulphur dioxide (SO2) and particulate matter (PM) also have negative external impacts as they contribute to climate change or cause local pollution. The same holds for contrails and the cirrus-like clouds that can arise from them. Additionally, emissions of NOx, SOx, and PM have a negative impact on local air quality. There are various studies that quantified the external costs of PM and NOx on local air quality (UK DEFRA, 2021).

Noise

Aircraft noise production has negative impacts on the wellbeing and health of local residents. The negative impacts are caused by annoyance impacts, as well as health impacts. The Handbook on the external costs of transport provides valuations per person per year within a certain noise contour. Moreover, the Handbook derives costs per passenger or per flown km to estimate average noise costs for a flight (CE Delft, 2019).

Safety

Aviation safety is the key mission of ANSPs and the foundation of global aviation. Safety is an overriding objective under the SES performance scheme (European Commission, 2019a). For this reason, literature on valuation of safety is relatively limited (D'Appolonia, 2010). Safety aspects can be monetised through valuation of avoided fatalities, avoided injuries, airframe losses and avoided property damage (FAA, 2020; EUROCONTROL, 2020b). Notwithstanding the profound importance of aviation safety, there is a substantial lack of knowledge concerning metrics and methodologies to address trade-offs with other key performance areas (BLUE MED, 2020).

Recommendations and conclusions

In the industry commitment towards achieving net-zero emissions in European aviation, the sector needs to reduce emissions across all possible angles. According to Destination 2050, improvements in ATM and operations may yield a reduction of 6% of CO_2 emissions from aviation, of which a large part can be achieved in the short or medium term (NLR & SEO, 2021). To achieve these savings, cross-sector collaboration is imperative. Decision-making in or about ATM or aircraft operations should be based on maximising social benefits, rather than being an outcome of optimizing a set of KPIs for each individual stakeholder.

A social cost-benefit analysis framework (SCBA) allows to address the problem of interdependencies and diverging stakeholder priorities by expressing different impacts in monetary values. Such a framework – or the underlying approach – might be helpful in designing and setting effective performance indicators, policies, regulations and other measures. These, too, should be ultimately targeted at maximising the societal benefits.

Current environmental KPIs as defined in the SES Performance and Charging Scheme do not do so and even market-based measures that put a price on CO_2, such as the EU Emissions Trading System, might not meet that objective. As each of these two stimuli targets only one actor in the system (the ANSP or the aircraft operator) or focus on part of the problem (airspace efficiency or CO_2 emissions), they cannot stimulate the required collaboration, and do not necessarily steer towards the broader societal optimum. Future research and policymaking efforts should aim towards revising existing or designing additional KPIs based on a similar approach to analysing social costs and benefits as presented in this paper. The fact that that desired outcome is clear, does not make the path straightforward. Without information on the fuel burn of an aircraft, ANSPs cannot be expected to prioritise (re-)routings based on lowest CO_2 emissions, and without more flexible use or airspace or improved meteorological predictions, airspace users cannot be expected to always fly a fuel-optimal route – especially if ANS charges incentivise another path. A key priority should be to enable actors to oversee the full (holistic) impact of their choices and use these insights in their decision making. That could for example be achieved by better data sharing and increased trust between different stakeholders. Ex-post evaluation schemes, using which particular actors which have sacrificed their own performance interests to enable a more socially beneficial outcome, might also be a path worth exploring.

To further steer how actors resolve interdependencies, guidance of (local) authorities should ideally be streamlined. In addressing the trade-off between noise and CO_2, the former impacts could for example be prioritised up to a certain flight level (Ministry of Infrastructure and Water Management, 2020), while focussing on the latter above that altitude. A similar approach could be followed to address interdependencies between CO_2 and local air quality. Again, such decisions should be made holistically, in which an SCBA approach can clarify to what extent lowering noise exposure, for example, increases global warming.

With clear goals set out in the European Green Deal and the European Climate Law and an industry committed to reducing aviation emissions, all stakeholders have a strong incentive as well as an intrinsic drive to make sustainable aviation a reality. The key challenge of every step on the way there, is to make decisions that contribute to a meaningful holistic improvement, rather that choices that only contribute to further lock-in of the fragmented system that we know today.

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