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Benefits Analysis of Wind-Optimal Operations For Trans-Atlantic Flights

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North Atlantic Tracks are trans-Atlantic routes across the busiest oceanic airspace in the world. This study analyzes and compares current flight-plan routes to wind-optimal routes for trans-Atlantic flights. The historical flight track data recorded by EUROCONTROL's Central Flow Management Unit is merged with data from FAA's Enhanced Traffic Management System to provide an accurate flight movement database containing the highest available flight path resolution in both systems. The combined database is adopted for airspace simulation integrated with aircraft fuel burn to simulate traffic within the Organized Track System (OTS). The fuel burn for the tracks in the OTS are compared with the corresponding quantities for the wind-optimized routes for a month to evaluate the potential benefits of flying wind-optimal routes in North Atlantic Airspace. The potential fuel savings depend on existing inefficiencies in current flight plans, atmospheric conditions and location of the city-pairs. The potential benefits are compared with actual flight tests that have been conducted since 2010 between a few city-pairs in the trans-Atlantic region to improve fuel consumption.

I. Introduction

The cruise phase of the aircraft uses majority of the fuel consumed and airline operations have focused on reducing the cost of fuel and crew time during this phase of flight. Currently, aircraft cruise along a horizontal route following a predetermined altitude and speed profile. The selection of the horizontal route, altitude and speed profiles is made to accommodate several factors like terminal area constraints, congested airspace, restricted airspace and weather disturbances. The resulting aircraft trajectory consumes more fuel and produces more emissions than optimal four-dimensional trajectories. Several studies have described the inefficiencies of the current routing structure and benefits that can be realized by enabling technology to move towards wind-optimal routes.[1-4] A recent study using air traffic data covering flights to/from the top 35 airports in the continental United States during 2007 estimated that the routes used by aircraft were 2.9% higher than the direct routes between these city-pairs. The corresponding figure for traffic between the top 34 city-pairs in Europe was 4%[5]. The development of the ground support system has not kept up with the advances in aircraft avionics. The extra distance travelled over direct routes is significantly higher over US-Europe oceanic airspace due to lack of radar surveillance, VHF radio communication coverage and general reliance on procedural separation. Similarly flights from Europe to Asia suffer large excess track distances due to large restricted airspace, strict entry/exit points and terrain.

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The Asia and Pacific Initiative to Reduce Emissions (ASPIRE)[6] is a joint collaboration between the FAA and air navigation service providers (ANSP) in Australia, New Zealand, Singapore, Japan and Thailand. ASPIRE conducted a series of flights in 2008-2011 to successfully demonstrate the potential for fuel and emissions savings in the region. These flights made several changes to gate-to-gate operations, including reduced separation, more efficient flight profiles and tailored arrivals. The best practices from these flights are made available daily to all equipped aircraft on some city pairs between the United States and the Asia Pacific region. During 2011, the FAA, the European Commission, several European ANSPs and 40 European airlines participated in an effort to demonstrate NextGen and SESAR capabilities on trans-Atlantic flights. For the Atlantic Interoperability Initiative to Reduce Emissions (AIRE)[7], Air France flew several flights between New York JFK and Paris Charles De Gaulle airports as well as between Paris Orly and Guadeloupe Pointe-a-Pitre airports during 2010-2011. The flights used procedures designed to reduce environmental impact with no special equipage and reduced fuel usage by 600 to 900 kg per flight.

The North Atlantic Tracks (NAT)[8] are trans-Atlantic routes across the busiest oceanic airspace in the world and carried approximately 460,000 flights during 2012. Most flights operate at cruise altitudes varying from 29,000-41,000 feet. Current air traffic control requires a higher aircraft separation standard in the oceanic region due to limited radar surveillance. Figure 1 shows the north Atlantic airspace made up of the control areas, Reykjavik, Sonderstrom, Shanwick, Gander, Santa Maria and portion of New York Oceanic Center. The airspace is congested at peak hours because of the large horizontal separation criteria and a narrow range of fuel-efficient flight levels. The NAT air traffic can be classified into two major flows as a result of passenger demand, time zone differences, and airport noise restrictions. They are the westbound flow departing Europe in the morning and the eastbound flow departing North America in the evening. A system of tracks known as the Organized Track System (OTS) is constructed to increase the throughput and efficiency of NAT air traffic system by aligning the air traffic flows with their minimum time tracks and altitude profiles. Figure 1 plots a set of westbound tracks in magenta lines and eastbound tracks in cyan lines. Eastbound and westbound minimum time tracks are seldom identical in the presence of jet streams. Separate organized track structure is therefore created and published daily for each of the major flows.

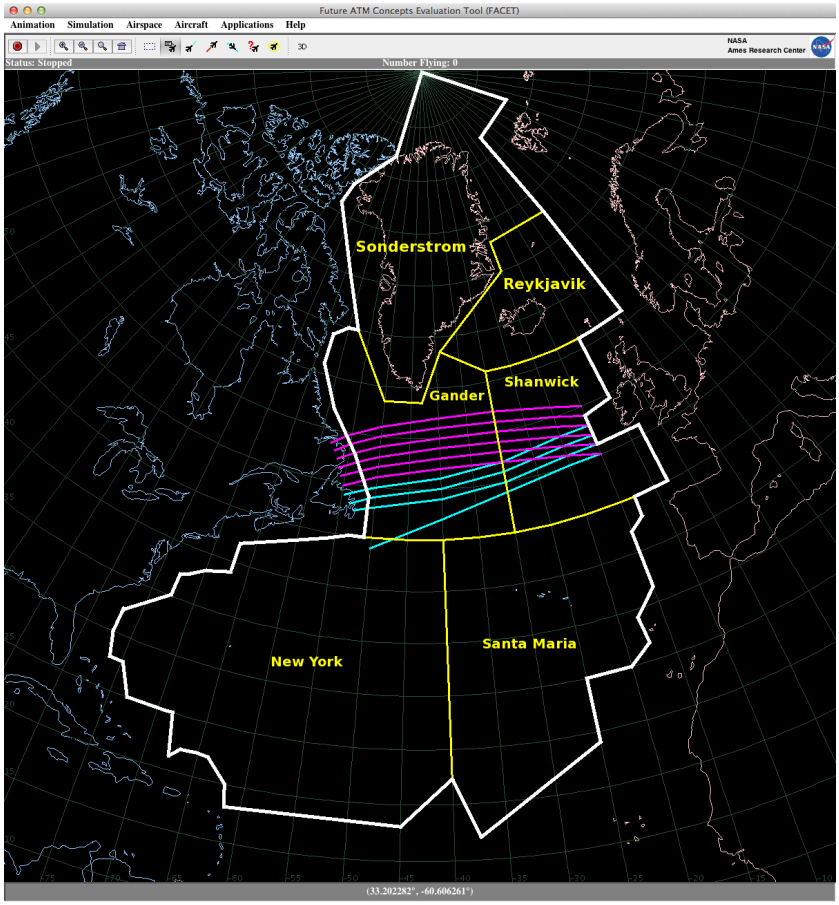

Fig.1. North Atlantic Airspace with OTS and Oceanic control areas.

A recent study[9] examines the effect on the current traffic situation in NAT due to reduction of the separation standard as a result of implementing the Automated Dependent Surveillance-Broadcast (ADS-B) technology. Reducing the separation standard potentially raises the total number of flights and reroutes in NAT. It shows that the total flight duration decreases significantly when more aircraft fly the minimum time trajectories through re-routing within the track system. No study has evaluated either the potential benefits of flying wind-optimal routes for the NAT air traffic or investigated the impact to the eastbound and westbound minimum time tracks within OTS due to environmental considerations.

This study evaluates the potential benefits of flying wind-optimal routes in NAT with respect to the fuel efficiency and emissions. A combined database that merges historical flight track data recorded by EUROCONTROL's Central Flow Management Unit (CFMU) with data from FAA's Enhanced Traffic Management System (ETMS) is developed to provide an accurate flight movement database for historical trajectory simulation for trans-Atlantic flights. A trajectory optimization algorithm[10] is applied for trans-Atlantic flights in cruise to generate wind optimal aircraft trajectories. Flying wind-optimal heading minimizes aircraft travel time, fuel burn and associated emissions during cruise. The wind-optimal routes are compared to the minimum time tracks in NAT oceanic airspace to estimate the potentials for fuel savings and reduce inefficiencies in cruise flight.

Section II presents aircraft trajectories simulation for trans-Atlantic flights. Section III describes the computation of the wind-optimal routes. Section IV analyzes trans-Atlantic aircraft flying several different routes. Conclusions and future work are described in Section V.

II. Flight Simulation

A method was developed for the generation of a common flight movement database of north Atlantic air traffic. To study the optimization potential of north Atlantic flight routings with respect to fuel burn and climate impact a database has to be created that contains flight route information that can be analyzed with actual weather data. The routes used by airlines today can be generated by simulating flight along the proposed flight plan or by using the actual flight tracks. These two approaches are described below.

A. Flight Plan Route

Prior to takeoff airline dispatchers have to file a flight plan providing aircraft specific information, route data, as well as the mass distribution and required amount of fuel. This information typically is provided in forms that have been standardized by International Civil Aviation Organization (ICAO). For example, the field 15 of such a flight plan form contains a route string made up of different airways, intersections and other navigation aids that uniquely define the planned lateral flight movement with respect to the ground. Furthermore, this string can contain information on the locations of possible considered altitude and speed changes for the sake of enhancing the vertical flight profile in terms of optimum flight performance. An exemplary field 15 flight plan route for a flight from Dallas/Fort Worth to Paris Charles de Gaulle is shown below:

N0459F350 TRISS4 TXK J131 PXV DCT CVG DCT APE DCT EWC DCT ETG DCT FQM DCT LHY DCT IGN DCT PUT J42 BOS DCT BRADD DCT COLOR/M078F370 NATY ETIKI/M078F370 UN480 REGHI/N0452F370 UN482 KURIS/N0420F270 UN482 ANG UN741 KEPER

Within this example string the Air Traffic Service (ATS) route designator, NATY is special to flights going through the North Atlantic airspace. Flights from North America to Europe and vice versa typically fly along the NAT that are issued daily based on the predominant weather (especially wind) situation. The NATY, which is referred to in the above shown flight plan string, is defined in terms of latitude/longitude waypoints that will be different for various wind patterns. Thus, dispatchers can repeatedly use the same flight plan but the route defined by it might vary from day to day.

To simulate a flight (e.g. with a trajectory simulator) in order to analyze its fuel and flight time, the field 15 route string has to be resolved in terms of the individual waypoints defined by latitude/longitude coordinates. This was achieved by a route translation function that provides a list of latitude/longitude pairs for a given route string. This function analyzes the string element-wise and looks up the corresponding ATS routes and navaids by accessing the European Aeronautical Database (EAD) maintained by EUROCONTROL containing navigational ARINC cycle data covering a large area of the world's aviation infrastructure. Each ATS route designator can thus be substituted by the representing waypoints between the adjacent intersections.

B. Actual Flight Track

As an alternative to the planned route data contained in the ICAO flight plan field 15, which is the planned route that is considered in strategic and pre-tactical planning horizons but does not contain any ad-hoc route deviations, e.g. due to weather or aircraft avoidance measures commanded by Traffic Alert and Collision Avoidance System (TCAS) or ATC, actual/historical flight track data can be used to describe an aircraft's lateral flight path. Possible sources for such track data are point profiles recorded by EUROCONTROL's Central Flow Management Unit (CFMU) and the corresponding US recorded flight tracks in FAA's Enhanced Traffic Management System (ETMS). The CFMU data features a higher track resolution in the European airspace, referred to as European Civil Airspace Conference (ECAC) space, while using great circle interpolation in the North American airspace. ETMS data is observed to be far more accurate in the National Airspace System (NAS) while showing deficiencies in the ECAC space. The flight track resolution in the North Atlantic airspace is comparable in both systems since it mainly consists of waypoints defining the selected North Atlantic Track. Thus, combining the two complementary databases leads to an accurate flight movement database containing the highest available flight path resolution in NAS and ECAC. Any point along the intermediate NAT can be used as the interface point where both datasets have to be merged. A similar approach has been used before within the project AERO2K[11].

Figure 2 shows an exemplary flight from Orlando, FL (KFSB) to Glasgow, UK (EGPF). In the figure the blue line depicts point profile data from EUROCONTROL while the black line represents the track data taken from ETMS. It can be recognized that by merging both databases more accurate flight track data can be obtained. This can be used as a more accurate reference for the assessment of the environmental goodness of flight routes or to increase the accuracy of the determination of aircraft emission distributions that can be used to create emission inventories.

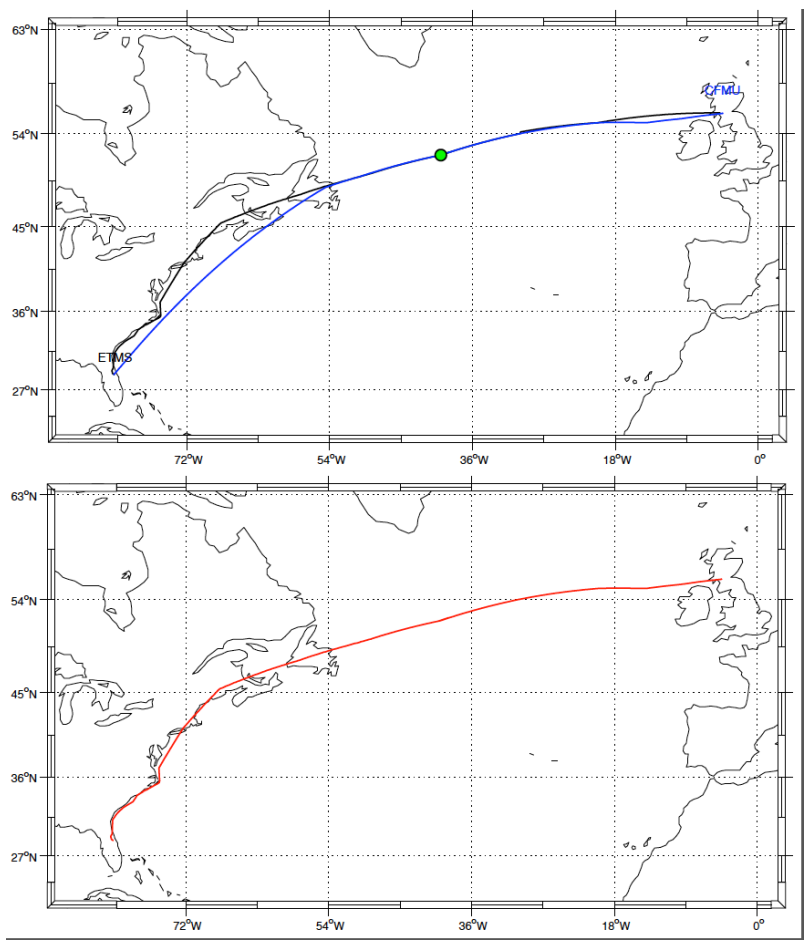

Figure 2: Track data for a flight from Orlando, FL (KSFB) to Glasgow (EGPF); top: the blue line depicts point profile data from EUROCONTROL, the black line represents the track data taken from ETMS, the green dot visualizes the merging point found by the matching algorithm; bottom: The resulting merged track is shown in red color.

The following methodology was used in the merging of the tracks. First, for a defined period recorded flight track data of trans-Atlantic flights was taken from FAA's ETMS database. For the same period, recorded point profiles were taken from EUROCONTROL's Demand Data Repository (DDR). These flight data were exported in SegOut6 (SO6) data format and filtered for those flight numbers not listed in the ETMS dataset. Since one particular flight number may occur more than once per day, additionally departure and arrival times were taken into account in order to uniquely identify the corresponding DDR flight.

For each flight, both tracks were analyzed with respect to their completeness and accuracy. Due to the point-based exporting mechanism applied to ETMS data, some tracks started en-route far from the original departure airport or ended distant from their destination (examples for such cases are flights that are already airborne at midnight on a given day). Since ETMS data should be used to enhance the data accuracy within the NAS, on westbound flights, tracks that start en route but end at the destination airport were considered complete. For eastbound flights, tracks had to start at departure airport but were allowed to end prior to reaching the destination in order to be considered complete. DDR flight track data has been exported using a flight-based mechanism (i.e. all flights that were airborne during the period of consideration were selected, no matter whether they departed the day before or land the next day). Therefore, the DDR dataset only contains complete flight tracks. Thus, whenever an ETMS flight was found to be incomplete it was fully substituted by the corresponding DDR track.

In all other cases, a matching algorithm has been applied, that identifies a point along both tracks that is best suited for merging the data. This algorithm performs track correlation searching for track segments where both tracks overlap. Along the segment with the strongest correlation the point with the highest closeness between both datasets is selected as merging point. The resulting merged track data finally consists of all ETMS points to the west of the merging point combined with all DDR points to the east of the detected merging point.

III. Wind-Optimal Trajectories

Wind-optimal flight paths were generated previously[10] by applying Pontryagin's Minimum Principle[12] to determine the optimal heading angle for aircraft during cruise. Earlier studies examine the travel time and fuel usage savings of transitioning from the fixed Central East Pacific routes to user-preferred routes through the development of minimum time wind-optimal routes using dynamic programming algorithm[13]. Trajectory optimization has been used to evaluate the potential benefits of flying wind-optimal cross-polar routes[10]. Following the development in[10], the horizontal trajectory is optimized by determining the heading angle that minimizes travel time in the presence of winds. The aircraft equations of motion at a constant altitude above the spherical Earth's surface are:

$$\dot{\phi} = \frac{V\cos\psi + u(\phi,\theta,h)}{R\cos\theta}, \tag{1}$$

$$\dot{\theta} = \frac{V\sin\psi + v(\phi,\theta,h)}{R}, \tag{2}$$

subject to the conditions that thrust equals drag, flight path angle is zero, and the boundary constraints are met. ϕ is longitude and θ is latitude, ψ is heading angle, and R is the Earth's radius. The East-component of the wind velocity is $u(\phi,\theta,h)$, and the North-component of the wind velocity is $v(\phi,\theta,h)$. It is assumed that the Earth is a sphere and $R >> h$.

The dynamical equation for the optimal aircraft heading[10] is:

$$\dot{\psi} = \frac{-F_{\text{wind}}(\psi,\phi,\theta,u,v,V)}{R\cos\theta}, \tag{3}$$

where $F_{\text{wind}}(\psi,\phi,\theta,u,v,V)$ is aircraft heading dynamics in response to winds and is expressed as:

$$
\begin{aligned}
&F_{\text{wind}}(\psi,\phi,\theta,u,v,V) \\
&= [-\sin\psi\cos\psi\frac{\partial u(\phi,\theta,h)}{\partial\phi} + \cos^2\psi\sin\theta\ u(\phi,\theta,h) + \cos^2\psi\cos\theta\frac{\partial u(\phi,\theta,h)}{\partial\theta} - \frac{\partial v(\phi,\theta,h)}{\partial\phi} \\
&\quad + \sin\psi\cos\psi\sin\theta\ v(\phi,\theta,h) + \cos\psi\ \sin\psi\cos\theta\frac{\partial v(\phi,\theta,h)}{\partial\theta} + V\cos\psi\sin\theta + \cos^2\psi\frac{\partial v(\phi,\theta,h)}{\partial\phi}].
\end{aligned} \tag{4}
$$

Deriving the wind-optimal dynamical equation reduced the trajectory optimization problem from a two-point boundary value problem[12] to an initial value problem. Numerical algorithms such as collocation methods or interpolation techniques can be applied to determine the optimal initial aircraft heading. In the case that an aircraft cruises at a single altitude, the minimum-time trajectory is completely specified by integrating equations (1-4) simultaneously from the origin to the destination using the optimal initial aircraft heading. Note that the minimum-time trajectory is fuel-optimal for aircraft cruise at a constant altitude. Long flights typically change their cruise altitude en route. A practical approach to generating wind-optimal trajectories with multiple cruise altitudes is described in an earlier paper[14].

IV. Results

This section generates the wind-optimal trajectories for trans-Atlantic aircraft. The results are used to assess the potential fuel savings of the wind-optimal trajectories when compared to the flight trajectories based on actual flight tracks. Aircraft trajectories are computed using wind-data provided by Global Forecasting System (GFS). GFS is a global numerical weather prediction computer model run by the National Oceanic & Atmospheric Administration (NOAA) four times a day. It produces forecasts up to 16 days, and produces a forecast for every 3rd hour for the first 180 hours, and after that, every 12 hours. The horizontal resolution is roughly equivalent to 0.5×0.5 degree latitude/longitude. GFS data has 64 unequally spaced vertical isobaric pressure levels ranging between 0.25-1000 mb, with enhanced resolution at low and high altitude. Figure 3 shows wind-optimal trajectories for the trans-Atlantic flights at 36,000 feet at 6 a.m. EDT on January 1, 2012. The wind-optimal trajectories across North Atlantic Ocean can be classified into two major flows due to the presence of jet streams. The westbound flow originating from Europe is located north of eastbound flow originating from North America. NATs are designed daily aiming at aligning the trans-Atlantic traffic with the wind-optimal routes for increasing the throughput and efficiency of air traffic system.

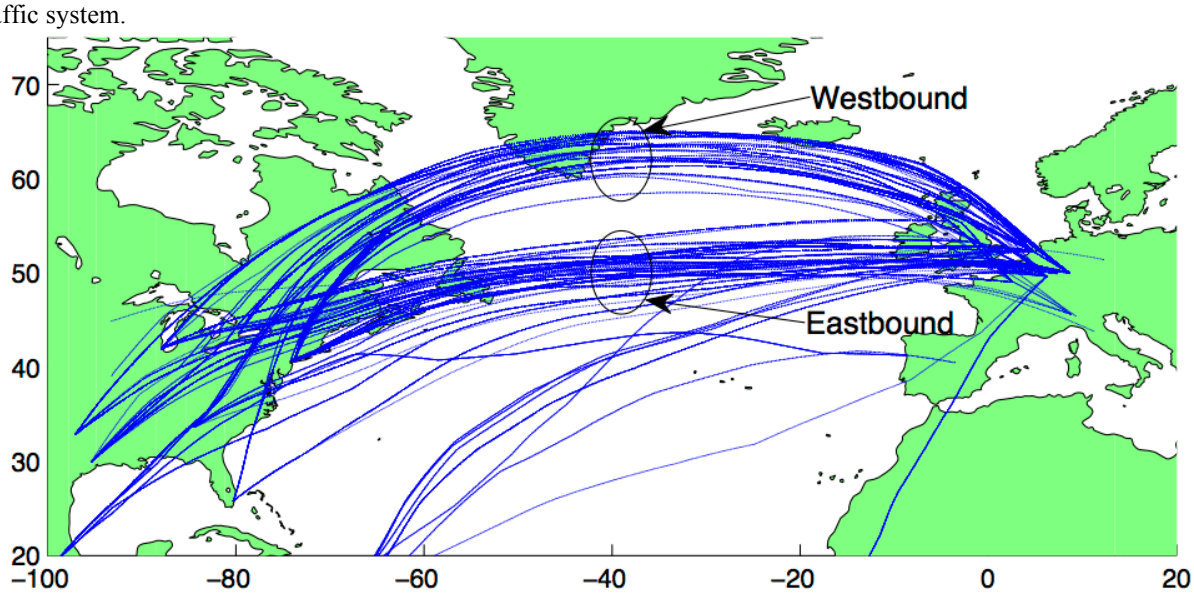

Figure 3. The wind-optimal trajectories for trans-Atlantic flights on January 1, 2012.

Section IVA discusses the setup for simulation of flight trajectories along the wind-optimal routes and the actual flight tracks for a trans-Atlantic flight from Newark, NJ to Frankfurt, Germany. Section IVB assesses the daily variations of potential wind-optimal savings for the westbound and the eastbound trans-Atlantic flights between Newark and Frankfurt. Section IVC presents the potential fuel benefits resulting from wind-optimal trajectories for the 10 busiest trans-Atlantic airport pairs. Section IVD ranks the top 100 airport pairs by most potential fuel savings.

The estimated mean fuel burn for the trans-Atlantic flight tracks and the potential fuel burn savings for the common aircraft types are presented for the 10 busiest trans-Atlantic airport pairs.

A. A Trans-Atlantic Flight from Newark to Frankfurt

Flight trajectories are simulated for a trans-Atlantic flight from Newark (KEWR) to Frankfurt (EDDF) based on the wind-optimal route, lateral flight track from ETMS and the merged flight track from both CFMU and ETMS as discussed in Section II, respectively. They are analyzed to understand the sensitivity of the performance evaluation due to the enhancements and approximations made in this study. The horizontal paths for the wind-optimal, ETMS track and the merged track are shown Fig.4. The wind-optimal trajectory is calculated at a constant cruise altitude same as the filed cruise altitude for the flight. In general, a long-haul flight performs en-route step climbs to the fuel-optimal cruise altitudes due to continuous aircraft weight reduction caused by aircraft fuel consumption. The flight simulation in this paper neglects the en-route step climbs since the optimal step climbs for the wind-optimal trajectory depends on the aircraft takeoff weight that is not available from the flight database, and the accuracy is also limited by the aerodynamic approximation adapted in the fuel burn model.

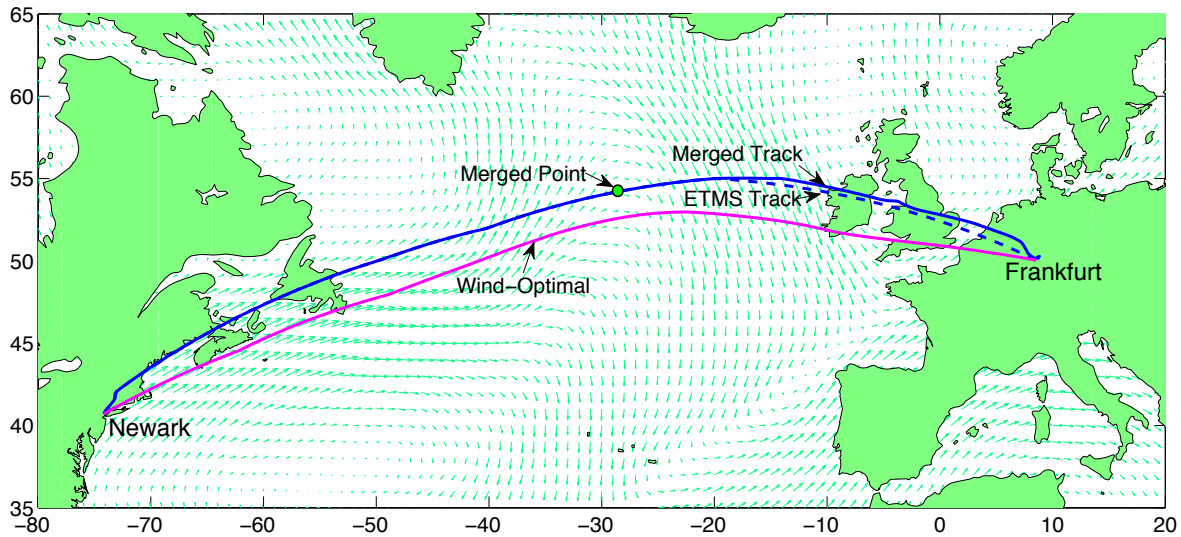

Figure 4. Horizontal routes based on wind-optimal trajectory and the actual flight tracks

Figure 5 shows the flight vertical profiles. The flight trajectories during initial takeoff, cruise and landing are simulated using the typical aircraft profiles for a Boeing 757-200 with medium takeoff weight based on Eurocontrol's Base of Aircraft Data Revision 3.6 (BADA)[15]. The travel time for the wind-optimal trajectory is 393 minutes and the fuel burn is 21,282 kg that saves potentially 1% and 2.3% fuel burn when compared to that of trajectories based on ETMS track and the merged track, respectively. The difference in the potential fuel savings resulting from the uncertainty in the flight tracks is roughly 1.3% in this example.

The flight trajectories are re-simulated by assuming the aircraft cruises from the origin to the destination. In this case, the travel time for the wind-optimal trajectory is 383 minutes and the fuel burn is 17157 kg that saves potentially 1.5% and 3% fuel burn when compared to that of trajectories based on ETMS-track and merged-track, respectively. The savings assessed based on the trajectories neglecting initial takeoff and landing are 0.5% to 0.7% higher then the assessment with takeoff and landing phases.

In addition to establishing a baseline for the current routes, a system-wide evaluation of the benefits of flying wind-optimal trajectories requires choices to be made in the selection of aircraft aerodynamic and fuel flow models. This is dictated by both the availability and accuracy of the models. The aircraft fuel flow models[15] used in this analysis perform well in cruise and later versions of the model have substantial improvements to fuel flow performance in climb and descent. The flight trajectories are simulated and compared for cruise phase only in the rest of the analysis. The flight tracks are based on both ETMS tracks and the merged tracks if available in the merged database as ongoing efforts are made for merging the flights recorded in ETMS and CFMU database. The uncertainty of estimated savings resulting from simplified aircraft simulation and imperfect flight track is approximately 1%.

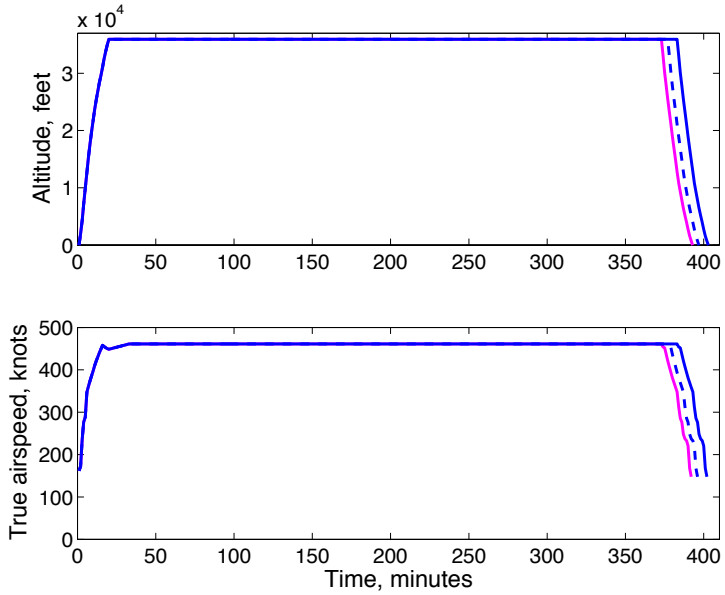

Figure 5. Vertical profiles for the three trajectories

B. Potential Savings Daily between KEWR and EDDF

The flight simulation is extended for all trans-Atlantic flights from Newark (KEWR) to Frankfurt (EDDF) during July 2012 based on the wind-optimal routes and the actual flight tracks. Figure 6 plots the potential fuel savings for the wind-optimal trajectories for each day during July 2012. The fuel burns are calculated based on aircraft type for all flights operating between the airport pair in the period. The potential wind-optimal savings are measured in terms of percent fuel reduction on average for the eastbound and westbound flights, respectively. The mean fuel savings for the entire month is 2.4% for the eastbound flights and 2.2% for the westbound flights. Eastbound flights have savings that varied from 0.5% to 8.1% with 1.8% standard deviation over the period. Westbound flights have a relatively narrow range between 0.5% and 4.2% with 1% standard deviation over the period. These results suggest that fewer westbound flights deviated far away from the wind-optimal routes. Note that westbound trans-Atlantic flights operate in the presence of strong head winds that are penalized with higher fuel burn for not flying optimal routes. The potential amount of fuel burn saved from wind-optimal route depends on the aircraft type and the direction of trans-Atlantic air traffic. These results will be investigated in Section IVD.

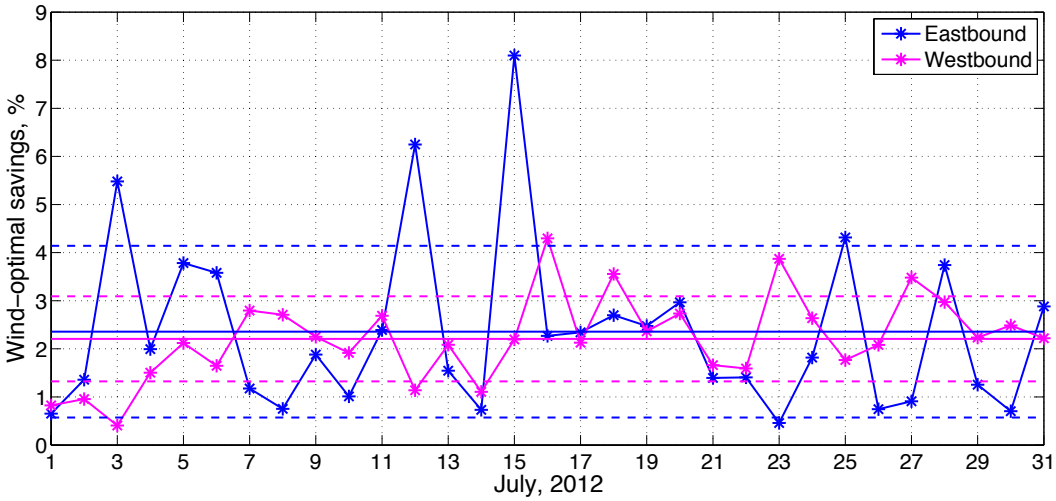

Figure 6. Potential fuel savings between KEWR and EDDF during July 2012.

The percent fuel savings varies depending on the air traffic and weather conditions over the period. The traffic patterns and the weather conditions for the days that have higher fuel savings identify conditions under which wind-

optimal operations provide higher benefits. The rest of the study extends current analysis to cover all trans-Atlantic flights operated in July 2012.

C. Potential Wind-optimal Benefits for 10 Busiest Airport Pairs

The wind-optimal and flight track-based trajectories are generated for trans-Atlantic air traffic for the entire month of July 2012. The results are used to assess the potential fuel benefits resulting from wind-optimal trajectories for various airport pairs and aircraft types over this period. A total of 30,354 trans-Atlantic flights, approximately 1000 per day, are selected for this study based on all the information needed to make the wind-optimal computations. There are 15,819 eastbound and 14,535 westbound flights for this month.

The 10 busiest airport pairs are listed in Table 1. The airports are ranked by the total number of eastbound and westbound flights. The trans-Atlantic air traffic for the 10 airport pairs includes a total of 2734 eastbound and 2759 westbound flights that constitute approximately 18% of total traffic. The aircraft types and the counts for the entire fleet are ranked and shown in the last two columns in Table 1. Note that performance parameters for Boeing 777-300ER are currently unavailable in the fuel burn model and those of Boeing 777-200 are used instead.

Table 1. Ten busiest airport pairs and common aircraft types for the trans-Atlantic flights during July 2012

Rank	Airport Pairs	East-bound	West-bound		Rank	Aircraft Types	Counts
1	New York (KJFK) – London (EGLL)	587	591		1	Boeing 767-300	5034
2	New York (KJFK) – Paris (LFPG)	324	306		2	Boeing 777-200	3945
3	Newark (KEWR) – London (EGLL)	308	306		3	Boeing 747-400	3513
4	Chicago (KORD) – London (EGLL)	303	308		4	Airbus A330-300	3044
5	Los Angeles (KLAX) – London (EGLL)	248	248		5	Boeing 757-200	2986
6	Boston (KBOS) – London (EGLL)	240	243		6	Airbus A330-200	2280
7	Washington, DC (KIAD) – London (EGLL)	186	235		7	Airbus A340-300	1298
8	Chicago (KORD) – Frankfurt (EDDF)	175	190		8	Boeing 767-400	1256
9	San Francisco (KSFO) – London (EGLL)	183	167		9	Airbus A340-600	1117
10	New York (KJFK) – Madrid (LEMD)	165	180		10	Boeing 777-300ER	789

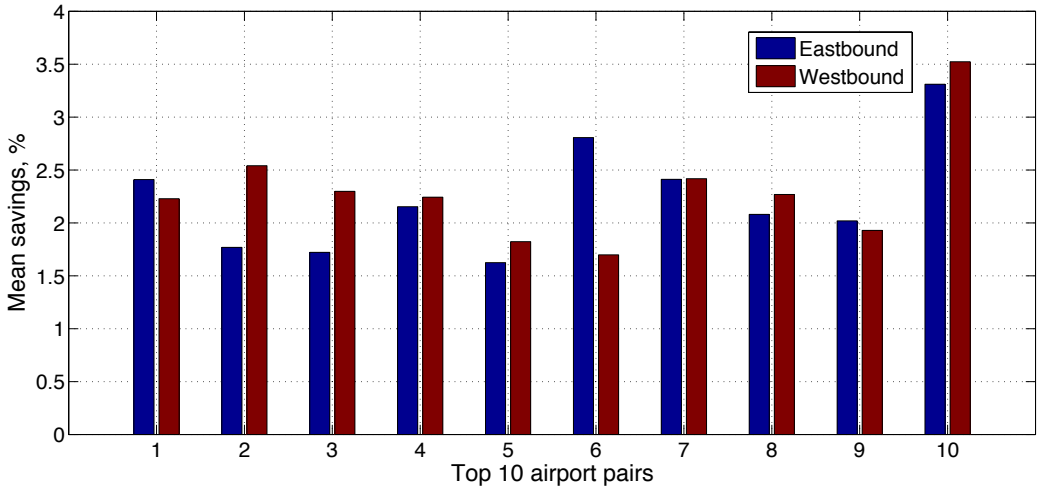

Figure 7. Mean fuel savings for flights between the 10 busiest city-pairs during July 2012.

The bar chart in Fig. 7 presents the potential wind-optimal savings in percent fuel reduction for the eastbound flights in blue bar and westbound flights in red bar, respectively. The monthly mean fuel savings for the ten airport pairs are between 1.6% and 3.3% for the eastbound flights and 1.7 and 3.5% for the westbound flights. These results provide an assessment of the route efficiency for the 10 city pairs. Westbound flights tend to have a slightly larger savings for these city pairs except for London-Boston. Westbound flights from London to Boston also have the smallest savings among the 10 city pairs. This may be due to London being close to the entry points of the westbound tracks and Boston being close to the exit points of the westbound tracks. The eastbound flights from Boston to London enter the eastbound tracks that are located relatively further south. These flights share the entry

points with trans-Atlantic flights departing from New York area and have a bigger potential for route improvement. The flights between New York and Madrid have the highest potential savings in the group. These flights may have relatively fewer wind-optimal tracks to choose since Madrid is located south of the major trans-Atlantic traffic flows. The results show that potential fuel savings increase for westbound flights as the latitude of the departure airport decreases. These results can be combined with typical fuel consumption for aircraft operating in these city pairs to estimate fuel burn savings resulting from flying the wind-optimal route for each flight.

D. Aircraft Fuel Burn and Potential Savings

The top 100 airport pairs that have most eastbound trans-Atlantic flights are identified from the track data. Then, they are sorted based on the potential fuel savings for July 2012. The results for westbound traffic are obtained similarly. Figure 8 plots the mean fuel savings in descending order for the top 100 eastbound airport pairs in blue and the top 100 westbound airport pairs in magenta. The 10 busiest airport pairs listed in Table 1 are also denoted in the figure. The range of potential savings for the eastbound traffic is between 10.6% and 1.5% while westbound traffic is between 5.8% and 1.4%. Note that actual savings will vary as simulation results are based on simplified aircraft trajectories using approximated flight tracks as mentioned in Section IVA.

These results provide an insight to the route discrepancies between the wind-optimal paths and the actual flight tracks. The trans-Atlantic flights operating between the high-ranked airport pairs have a higher potential for fuel savings resulting from flying wind-optimal routes. The potential fuel burns saved by these flights depend on the aircraft types operating in the fleet.

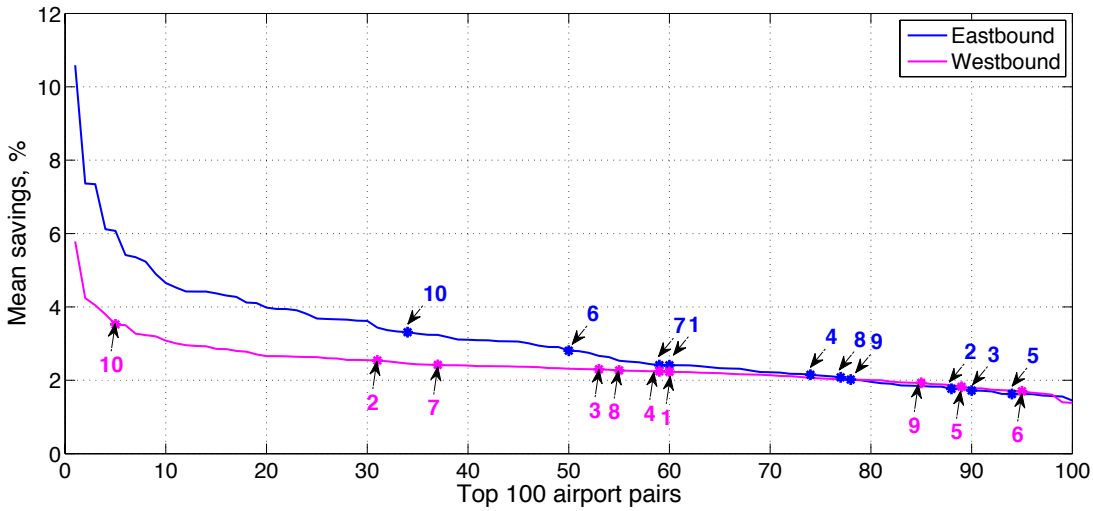

Figure 8. Mean fuel savings ranked for the top 100 busiest city-pairs during July 2012.

Aircraft fuel burn are estimated for the trans-Atlantic flights based on the flight tracks between the 10 busiest airports in July 2012. The mean fuel burn, expressed in units of 1000 kg (metric ton), for each aircraft type identified in the fleet are provided in Table 2. The abbreviation "n/a" indicates an aircraft type not used for some city pair combinations. The eastbound trans-Atlantic flights from KJFK to EGLL using aircraft type 2, Boeing 777-200, consume 31.3 metric tons of fuel. The aircraft type 3, Boeing 747-400 and type 9, Airbus A340-600 has higher average fuel burns compared to others in the group. In general, the westbound flights have higher fuel consumption than the eastbound flights in the presence of winds.

The fuel burn values are applied for estimating amount of fuel saved by each aircraft type combining aforementioned percent fuel savings for each airport pair. For example, eastbound flights from KJFK to EGLL, which has an estimated savings of 2.42%, can potentially save 31,300 kg×2.42% = 760 kg fuel for aircraft type 2, Boeing 777-200. The fuel burn savings in kilograms for the busiest airports and the common aircraft types in the fleet are listed in Table 3. Westbound flights between all airport pairs except KBOS-EGLL potentially save more fuel due to higher fuel burn for the westbound traffic. The eastbound flights for KBOS-EGLL save more fuel because of a much larger percent fuel savings as shown in Fig. 7. The high-ranked airports and the high-ranked aircraft types as presented in the upper left corner of Table 3 indicate trans-Atlantic flight operations with high frequency. Combing frequency of flights with potential fuel savings between city pairs identifies a set of flights that provide wind-optimal operations with most fuel reduction across the Atlantic Ocean.

Table 2. Mean fuel burn in metric tons based on flight tracks for the top 10 busiest airports and the widely used aircraft types during July 2012.

Airport Pairs		Aircraft Types								
Rank	Direction	1	2	3	4	5	6	7	8	9
1 KJFK-EGLL	Eastbound	n/a	31.3	44.2	27.6	n/a	n/a	28.9	23.9	37.1
	Westbound	n/a	36.5	50.3	31.9	n/a	n/a	37.0	27.6	44.3
2 KJFK-LFPG	Eastbound	23.7	32.4	n/a	28.9	16.7	27.3	31.7	n/a	n/a
	Westbound	28.0	39.5	n/a	34.4	19.5	31.7	37.6	n/a	n/a
3 KEWR-EGLL	Eastbound	22.7	31.2	42.4	n/a	16.0	n/a	n/a	n/a	36.7
	Westbound	26.6	36.3	49.6	n/a	18.5	n/a	n/a	n/a	43.3
4 KORD-EGLL	Eastbound	26.9	37.9	52.2	n/a	n/a	n/a	36.1	n/a	43.8
	Westbound	29.8	41.4	57.9	n/a	n/a	n/a	39.3	n/a	49.2
5 KLAX-EGLL	Eastbound	n/a	53.8	72.8	n/a	n/a	n/a	n/a	n/a	62.1
	Westbound	n/a	59.4	79.6	n/a	n/a	n/a	n/a	n/a	70.3
6 KBOS-EGLL	Eastbound	n/a	29.2	42.0	n/a	15.2	n/a	29.0	22.5	35.1
	Westbound	n/a	33.2	47.3	n/a	17.4	n/a	32.5	25.7	41.2
7 KIAD-EGLL	Eastbound	24.8	33.6	47.9	n/a	16.8	n/a	n/a	n/a	40.3
	Westbound	27.8	38.9	53.1	n/a	19.4	n/a	36.4	n/a	46.3
8 KORD-EDDF	Eastbound	n/a	41.7	56.5	n/a	n/a	n/a	39.6	n/a	n/a
	Westbound	28.2	45.4	61.3	n/a	n/a	n/a	43.3	n/a	n/a
9 KSFO-EGLL	Eastbound	n/a	53.7	71.6	n/a	n/a	n/a	48.8	n/a	61.1
	Westbound	n/a	57.7	77.8	n/a	n/a	n/a	52.6	n/a	65.8
10 KJFK-LEMD	Eastbound	23.5	n/a	n/a	n/a	17.0	26.2	33.1	n/a	41.0
	Westbound	27.5	n/a	n/a	n/a	19.3	31.0	37.8	n/a	46.9

Table 3. Potential fuel burn savings in kilograms for the busiest airports and the widely used aircraft types during July 2012.

Airport Pairs		Aircraft Types								
Rank	Direction	1	2	3	4	5	6	7	8	9
1 KJFK-EGLL	Eastbound	n/a	760	1070	660	n/a	n/a	700	580	900
	Westbound	n/a	810	1100	710	n/a	n/a	830	620	990
2 KJFK-LFPG	Eastbound	420	570	n/a	510	300	480	560	n/a	n/a
	Westbound	710	1000	n/a	870	490	810	950	n/a	n/a
3 KEWR-EGLL	Eastbound	390	540	730	n/a	280	n/a	n/a	n/a	630
	Westbound	610	840	1100	n/a	420	n/a	n/a	n/a	1000
4 KORD-EGLL	Eastbound	580	810	1120	n/a	n/a	n/a	780	n/a	940
	Westbound	670	930	1300	n/a	n/a	n/a	880	n/a	1100
5 KLAX-EGLL	Eastbound	n/a	870	1180	n/a	n/a	n/a	n/a	n/a	1000
	Westbound	n/a	1080	1450	n/a	n/a	n/a	n/a	n/a	1280
6 KBOS-EGLL	Eastbound	n/a	820	1180	n/a	430	n/a	810	630	990
	Westbound	n/a	560	800	n/a	300	n/a	550	440	700
7 KIAD-EGLL	Eastbound	600	810	1150	n/a	410	n/a	n/a	n/a	970
	Westbound	670	940	1280	n/a	470	n/a	880	n/a	1120
8 KORD-EDDF	Eastbound	n/a	870	1180	n/a	n/a	n/a	820	n/a	n/a
	Westbound	640	1030	1400	n/a	n/a	n/a	980	n/a	n/a
9 KSFO-EGLL	Eastbound	n/a	1080	1450	n/a	n/a	n/a	990	n/a	1200
	Westbound	n/a	1110	1500	n/a	n/a	n/a	1020	n/a	1270
10 KJFK-LEMD	Eastbound	780	n/a	n/a	n/a	560	870	1100	n/a	1400
	Westbound	970	n/a	n/a	n/a	680	1090	1330	n/a	1650

E. Comparison with Flight Results

Several flight tests have been conducted since 2009 between a few city-pairs in the trans-Atlantic region to improve fuel consumption and reduce the environmental impact of aviation. Icelandair conducted 38 flights from Keflavik to Seattle saving approximately 80kg of fuel per flight. For the AIRE, Air France flew several flights between New York JFK and Paris Charles De Gaulle as well as between Paris Orly and Guadeloupe Pointe-a-Pitre

Airport during 2010-2011. The flights used procedures designed to reduce environmental impact with no special equipage. The gate-to-gate savings during these flights ranged from 600 to 900 kg per flight. The simulation presented in this paper shows average savings of 300 to 570 kg for eastbound (New York to Paris) flights and average savings of 490-1000 kg for westbound flights (Paris to New York) respectively. The potential benefits resulting from the simulation can be scaled by comparing them with the savings during actual flight tests between certain city-pairs that have been conducted since 2009. The results shown in this paper are consistent with the earlier simulation results and flight tests. The actual savings vary widely depending on city-pair, aircraft type and departure time. These results provide an upper bound on the potential savings due of wind-optimal routes. The savings may be further reduced due to oceanic separation requirements and controller workload requirements.

V. Conclusion

A combined database is developed for merging the historical flight track data recorded by Eurocontrol Central Flow Management Unit and data from Enhanced Traffic Flow Management System to provide an accurate flight movement database containing the highest available flight path resolution in both systems. The flight plan routes and track data from this database are used in an airspace simulation integrated with aircraft fuel burn. The potential benefits of flying wind-optimal routes in North Atlantic Airspace are determined by comparing various quantities between baseline track performance and wind-optimal performance. The savings provide an upper bound on the benefits of oceanic wind-optimal operations and are consistent with savings recorded during limited flight tests. The results will be expanded by increasing the simulation period to a year, evaluate the changes in the benefit pool due to uncertainties in the fuel models by using later versions of BADA and by performing step climbs during cruise. As the airlines are equipped to generate and fly wind-optimal routes, a more detailed analysis may point to city-pairs and periods where factors other than wind-optimality as the big source of inefficiency in the routing of the aircraft. The combined database and the ability to generate wind-optimal routes under constraints provides inputs to an airspace simulation integrated with aircraft fuel burn and emissions models, contrail models, simplified climate response models, and a common climate metric to assess the climate impact of flight routes within the North Atlantic Organized Track System.

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