Environmental Modeling of Trans-Arctic and Re-routed Flights

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Recent work by researchers at Stanford University showed potentially large impacts on Arctic temperature increases due to aircraft over-flights. The FAA's Office of Environment and Energy tasked the Volpe Center, the MITRE Corporation, and Stanford with conducting an analysis of potential impacts of re-routing aircraft away from the Arctic region. This report discusses the methods used in developing the alternative cases used in the analysis. This report also presents the primary fuel consumption and oxides of Nitrogen emissions for the major Origin-Destination city pairs, airlines, and aircraft types identified in MITRE's analysis.

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1. Introduction

On April 10, 2009 researchers from Stanford University gave a presentation entitled "Aircraft Emissions and Arctic Polar Climate Impacts" to the FAA's Office of Environment and Energy (AEE). Their presentation included data that showed that aviation emissions contribute 20% of the arctic polar region warming trend, even though aviation's global contribution to green-house gases (GHG) is on the order of 3% of all anthropomorphic sources. The aircraft operations data source for Stanford's analysis was global flight data for the years 2004 and 2006 extracted from the Volpe Center's Enhanced Traffic Management System (ETMS) database [Ref. 1].

To improve the FAA's understanding of the impacts of aviation on climate change in the arctic region, AEE tasked the Volpe Center, the MITRE Corporation, and Stanford with providing an analysis of the costs and benefits of flight operations in the arctic region. The baseline case of the analysis is a more current year's operations in the arctic region, with as-flown operations. The alternative case of the analysis is same year's operations, but with the flight trajectories modified to avoid the arctic region.

This report is complimentary to MITRE Technical Report 090408 [Ref. 2]. The MITRE report discusses the baseline and MITRE's trajectory modification processes for the alternative, and the flight times and distances by Origin-Destination (O-D) pair, aircraft type, and operator of those two cases. This report presents the fuel consumption and emissions data for the baseline and alternative cases. As of the writing of this report, Stanford is conducting an analysis of the two cases to determine their estimated impacts on the warming trend in the Arctic region.

2. Data Collection

The first step in the analysis process was deciding which calendar year to use for the basis for the analysis. The two most recent years available in the ETMS database were 2006 and 2008. Both of these years contain a full set of U.S. operational data. If ETMS availability were the only consideration, then 2008, being the more recent, would have been the preferred choice. However, the 2006 dataset also contains the Enhanced Tactical Flow Management System (ETFMS) data from EUROCONTROL and operations in the International Official Airline Guide (IOAG). Volpe Center staff has integrated the ETMS, ETFMS, and IOAG data for 2006 so these data can be treated as a single data set. This 2006 data set has been used in support of prior studies, notably various analyses by the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP). The ETFMS data from 2008 were not available at the time of this study. In addition, the economic downturn at the end of 2008 reduced air travel activity in the final months of that year – the FAA and the modelers considered this reduction in operations to be unrepresentative of the general long-term trends in air travel.

The modelers decided, with FAA concurrence, that the 2006 data would be used as the basis for this study. Note that where ETMS or ETFMS data are not available, such as on trans-Pacific routes, IOAG information was used as the data source for operations. Those operations where radar-based data were not available were modeled by MITRE using their trajectory processer, combined with data from Volpe to estimate the use of en-route step-climbs and final cruise altitudes. This process is discussed in detail in the MITRE report.

3. Data Refinement

The modelers made a number of refinements to the data set; some to improve the quality of the analysis, others to simplify the analysis without materially reducing the quality.

One refinement was the addition of wind speed data into the analysis. The MITRE process involved modifying the trajectories on the polar re-routes to take advantage of the best available winds. Because the FAA's Aviation Environmental Design Tool (AEDT) does not use en-route wind information explicitly, the wind data were incorporated in AEDT by substituting the air-distance flown for the ground distance in the trajectory data. This method keeps the airspeed information unmodified (which is needed to determine the correct fuel consumption rates), and approximates the wind effects by modifying the distance flown.

Other refinements involved removing a number of operations from the database because the modelers believed retaining them either contributed little to the final analysis or would not be considered in any final implementation of a trans-Arctic flight regulation. The following are the categories of operations removed from the analysis:

3.1. O-D pairs

We began the analysis by deciding which O-D pairs to include in the analysis. After iteration on the process by FAA, MITRE, and Volpe, the team decided the re-route analysis would include flights with a northern-most point in their Great Circle trajectory above 50 degrees North latitude. Flights below this latitude would be unlikely to ever reach the Arctic Circle, even with operational consideration (e.g. favorable winds) that might encourage the aircraft to fly at a more northern latitude.

We eliminated from this analysis any city pairs where either the Origin or the Destination airport is above the Arctic Circle. This assumes that any restriction on trans-polar flights would not eliminate air transportation to those cities within the Arctic region. We also eliminated from the analysis all O-D pairs where one of the airports was the most northern point on the Great Circle trajectory; these pairs would be unlikely to be candidates for re-routing due to the predominantly north-south orientation of the trajectory.

We also considered flights less than 500 nautical miles to be too short to be effectively re-routed; these flights were also dropped from the re-routing analysis.

O-D pairs with less than 50 operations per year were also dropped from the re-route analysis. These O-D pairs represented less than 3% of the total operations, and their elimination from the analysis allowed a reduction in O-D pairs from 5015 to 1561. This reduction in O-D pairs was beneficial to the analysis since the trajectory development process involved manual steps; reducing the number of O-D pairs reduced the analysis demands on the modelers.

3.2. Aircraft types

We eliminated from re-route analysis those flights made by aircraft with less than 50 seats, as well as all turboprop and piston-engine aircraft. These aircraft were culled from the analysis since these are normally short range aircraft which probably could not be re-routed efficiently, or are General Aviation aircraft with few operations in the Arctic region. The combination of these aircraft (turbo-props, pistons, and jets with less than 50 seats) comprised less than 5% of the flights under consideration. All military flights were also removed from the analysis.

4. Modeling Process

The trajectory data for all the trans-arctic flights under consideration in this project were processed through AEDT. AEDT is the FAA's next-generation aviation environmental analysis tool suite; AEDT will replace the FAA's legacy noise analysis tools (the Integrated Noise model - INM, the Noise Integrated Routing System- NIRS, and the Model for Assessing Global Exposure to the Noise of Transport Aircraft - MAGENTA), and the emission and fuel consumption tools (the Emission and Dispersion Modeling System - EDMS, and the System for assessing Aviation's Global Emissions - SAGE). AEDT is currently under development by a single team whose members individually developed the FAA's legacy tools. For this analysis, the primary components of AEDT used were the Aircraft Performance Module (APM) and the Aircraft Emissions Module (AEM). The version of AEDT used in this study was the same as that used in a recent NASA Research Agreement (NRA) study on NextGen impacts on the National Airspace System (NAS), as well as the ICAO CAEP studies mentioned above.

The APM uses standard aircraft performance models based on the Society of Automotive Engineers Aerospace Information Report 1845 [Ref. 3] and EUROCONTROL's Base of Aircraft Date (BADA) [Ref. 4] to calculate the state parameters of each aircraft along its trajectory. The fuel consumption model in AEDT is based on that found in BADA, with augmentation by an additional terminal area model [Ref. 5]. The AEM uses the fuel flow and aircraft and flight environment state outputs of the APM to calculate emissions based on the Society of Automotive Engineers Aerospace Information Report 5715 [Ref. 6].

The outputs of the AEDT for the two cases are the aircraft's state parameters, including emission rates, along each segment of the flight path of each operation. These segment-level data were given to Stanford for further analysis of their climate impacts on the arctic region. In addition to the flights modeled in this analysis, all other flights (i.e. those not part of this analysis) were also sent to Stanford. The Stanford analysis will model all CY2006 flights; the flights in the CY2006 database which were not part of the re-route analysis were added back into both cases for the Stanford analysis. This was done so the Stanford climate model would work with a full set of global flights in both the trans-arctic and the rerouted case.

5. Modeling Results

The tables in this section present the fuel consumption and NOx emissions for those aircraft operations which were part of the analysis. Section 5.1 presents the fuel consumption data; Section 5.2 presents the NOx emissions data.

5.1. Fuel Consumption results

Table 1 below presents the total fuel consumption for all flights in each of the two cases, the baseline case and the trans-arctic re-route alternative.

Table 1. Total fuel consumption for all modeled flights

Fuel burn: Baseline (kg)	Fuel burn: Alternative (kg)	Difference (Alternative - Base) (kg)	Difference (%)
7,817,034,972	7,922,442,291	105,407,320	1.35%

5.1.1. Fuel consumption by O-D pair

The fuel consumption for those O-D pairs with more than 400 flights in 2006 is presented in Table 2 below. Note that this table corresponds to Figure 3-9 in the MITRE Report. The O-D pairs are listed in order of number of flights.

Table 2. Fuel consumption by O-D pair

O-D pair	Fuel Burn: Baseline (kg)	Fuel Burn: Alternative (kg)	Difference (Alt – Base) (kg)	Difference (%)
Heathrow to Narita (EGLL:RJAA)	201,035,756	202,985,907	1,950,151	0.97%
Heathrow to San Fran. (EGLL:KSFO)	183,559,760	186,072,183	2,512,423	1.37%
Heathrow to Los Angeles (EGLL:KLAX)	294,557,665	296,025,907	1,468,242	0.50%
Narita to Heathrow (RJAA:EGLL)	135,524,998	138,787,878	3,262,880	2.41%
Narita to Paris (RJAA:LFPG)	238,071,285	232,380,131	-5,691,154	-2.39%
Heathrow to Vancouver (EGLL:CYVR)	79,492,935	80,877,208	1,384,273	1.74%
Narita to Frankfurt (RJAA:EDDF)	130,842,331	137,292,855	6,450,524	4.93%
New York to Narita (KJFK:RJAA)	200,686,681	204,948,148	4,261,467	2.12%
Narita to Schiphol (RJAA:EHAM)	103,406,492	108,920,126	5,513,634	5.33%
New York to Incheon (KJFK:RKSI)	140,740,684	143,017,125	2,276,441	1.62%
Paris to Narita (LFPG:RJAA)	207,334,846	207,427,617	92,771	0.04%
Frankfurt to San Fran. (EDDF:KSFO)	85,264,106	89,792,644	4,528,538	5.31%
Chicago to Pudong (KORD:ZSPD)	73,537,612	75,822,116	2,284,503	3.11%
Paris to Los Angeles (LFPG:KLAX)	101,077,542	101,476,913	399,371	0.40%
Chicago to Hong Kong (KORD:VHHH)	97,507,868	101,136,001	3,628,133	3.72%
Frankfurt to Los Angeles (EDDF:KLAX)	103,659,777	104,635,327	975,551	0.94%
Heathrow to Calgary (EGLL:CYYC)	26,655,614	27,760,037	1,104,423	4.14%
Frankfurt to Narita (EDDF:RJAA)	147,796,033	147,089,215	-706,818	-0.48%
Heathrow to Seattle (EGLL:KSEA)	40,939,081	41,746,907	807,826	1.97%
Kansai to Schiphol (RJBB:EHAM)	54,858,643	55,875,736	1,017,093	1.85%

5.1.2. Fuel consumption by airline

The fuel consumption of the modeled flights for the major airlines (250 or more flights) is presented below. Note that these data correspond to Figure 3-10 in the MITRE Report. The airlines are listed in order of the sum of the number of their flights.

Table 3. Fuel consumption by major airline

Airline	Fuel Burn: Baseline (kg)	Fuel Burn: Alternative (kg)	Difference (Alt – Base) (kg)	Difference (%)
Japan Airlines (JAL)	653,429,460	662,054,219	8,624,759	1.32%
British Airways (BAW)	695,551,681	702,803,635	7,251,954	1.04%
Lufthansa (DLH)	705,462,217	714,652,370	9,190,152	1.30%
United Airlines (UAL)	772,722,712	783,329,363	10,606,651	1.37%
Air Canada (ACA)	401,142,342	410,618,420	9,476,079	2.36%
Air France (AFR)	468,908,496	468,401,303	-507,193	-0.11%
KLM	416,573,346	421,459,821	4,886,474	1.17%
Continental (COA)	278,120,154	286,732,370	8,612,217	3.10%
All Nippon (ANA)	335,978,912	337,983,212	2,004,300	0.60%
Korean Air (KAL)	359,990,849	364,182,627	4,191,778	1.16%
Virgin Atlantic (VIR)	298,271,983	299,811,228	1,539,245	0.52%
Demodedovo (DMO)	51,914,341	55,393,265	3,478,924	6.70%
America (AAL)	298,653,929	302,713,932	4,060,003	1.36%
Northwest (NWA)	408,504,996	410,539,606	2,034,609	0.50%
SAS	154,599,731	157,028,594	2,428,863	1.57%
Aeroflot (AFL)	73,562,161	74,241,351	679,190	0.92%
Yakutia (SYL)	19,410,169	19,985,718	575,549	2.97%
Nippon Cargo (NCA)	75,293,216	81,461,617	6,168,401	8.19%
Cathay Pacific (CPA)	82,723,125	85,247,702	2,524,577	3.05%
Swiss (SWR)	105,682,575	105,995,158	312,583	0.30%
Zoom (OOM)	23,422,401	23,752,565	330,164	1.41%
Delta (DAL)	107,368,442	107,565,916	197,474	0.18%
Air China (CCA)	123,556,635	132,177,171	8,620,536	6.98%
Cargolux (CLX)	79,873,256	81,588,543	1,715,288	2.15%
Air Transat (TSC)	28,044,314	28,308,737	264,423	0.94%
Finnair (FIN)	71,209,187	71,415,985	206,798	0.29%
Transaero (TSO)	11,617,339	12,725,348	1,108,009	9.54%
Singapore (SIA)	78,012,099	77,973,518	-38,580	-0.05%

5.1.3. Fuel consumption by aircraft type

The fuel consumption for the modeled flights of the major aircraft types (25 or more flights) is presented in Table 4 below. Note that the data in this table correspond to Figure 3-11 in the MITRE Report. The aircraft types are listed in order of their number of flights.

Table 4. Fuel consumption by major aircraft type

Aircraft Type	Fuel Burn: Baseline (kg)	Fuel Burn: Alternative (kg)	Difference (Alt – Base) (kg)	Difference (%)
B747-4	3,717,712,510	3,762,376,752	44,664,242	1.20%
B777-2ER	1,271,763,245	1,289,647,783	17,884,538	1.41%
A340-3	686,695,801	695,620,741	8,924,940	1.30%
B767-3ER	324,507,643	326,451,922	1,944,278	0.60%
A340-6	306,819,455	311,456,179	4,636,724	1.51%
B777-3ER	290,077,507	291,425,004	1,347,496	0.46%
A330-2	169,389,595	171,586,523	2,196,929	1.30%
A330-3	170,629,627	173,491,488	2,861,862	1.68%
TU154	30,560,016	31,492,237	932,221	3.05%
MD11	180,197,114	183,234,631	3,037,517	1.69%
A340-5	190,028,537	193,274,870	3,246,333	1.71%
IL62	37,385,646	40,058,942	2,673,297	7.15%
B777-2	119,693,456	121,025,143	1,331,687	1.11%
B767-2ER	29,324,428	30,630,017	1,305,589	4.45%
IL96	16,392,854	17,127,082	734,228	4.48%
B777-3	79,564,394	80,269,556	705,162	0.89%
B747-2	40,871,244	46,950,016	6,078,772	14.87%
B747-4ER	42,143,541	42,747,953	604,411	1.43%
A340-2	20,049,149	20,128,748	79,600	0.40%
TU204	8,175,956	8,222,230	46,274	0.57%
B737-8	1,188,438	1,222,009	33,571	2.82%
A310-3	2,445,251	2,488,775	43,524	1.78%
B757-2	11,687,852	11,677,641	-10,211	-0.09%
B767-3	14,082,757	14,102,261	19,504	0.14%
B767-2	1,837,299	1,890,726	53,426	2.91%
DC10-3	47,531,054	47,565,107	34,052	0.07%

5.2. Emissions results

Table 5 below presents the total NO_x emissions for all flights in each of the two cases, the baseline case and the trans-arctic re-route alternative. AEDT calculates numerous other emission types, such as CO_2, CO, SO_x, Hydrocarbons, and Particulate Matter; NO_x is given as an example.

Table 5. Total NOx emissions for all modeled flights

NO_x: Baseline (kg)	NO_x: Alternative (kg)	Difference (Alternative - Base) (kg)	Difference (%)
134,666,762	136,557,713	1,890,951	1.40%

5.2.1. Emissions results by O-D pair

The fuel consumption for the top 20 O-D pairs is presented in Table 6 below. Note that the data in this table correspond to Figure 3-9 in the MITRE Report.

Table 6. NO_x emissions by O-D pair

O-D pair	NO_x: Baseline (kg)	NO_x: Alternative (kg)	Difference (Alt – Base) (kg)	Difference (%)
Heathrow to Narita (EGLL:RJAA)	3,345,789	3,368,007	22,218	0.66%
Heathrow to San Fran. (EGLL:KSFO)	3,183,555	3,234,784	51,229	1.61%
Heathrow to Los Angeles (EGLL:KLAX)	4,964,996	4,992,763	27,767	0.56%
Narita to Heathrow (RJAA:EGLL)	2,245,809	2,295,763	49,955	2.22%
Narita to Paris (RJAA:LFPG)	4,468,706	4,307,065	-161,641	-3.62%
Heathrow to Vancouver (EGLL:CYVR)	1,349,672	1,377,804	28,132	2.08%
Narita to Frankfurt (RJAA:EDDF)	2,092,838	2,228,512	135,674	6.48%
New York to Narita (KJFK:RJAA)	3,823,752	3,926,046	102,294	2.68%
Narita to Schiphol (RJAA:EHAM)	1,672,716	1,789,284	116,568	6.97%
New York to Incheon (KJFK:RKSI)	2,516,744	2,564,673	47,928	1.90%
Paris to Narita (LFPG:RJAA)	3,665,773	3,654,766	-11,007	-0.30%
Frankfurt to San Fran. (EDDF:KSFO)	1,268,307	1,358,547	90,240	7.11%
Chicago to Pudong (KORD:ZSPD)	1,527,594	1,611,061	83,467	5.46%
Paris to Los Angeles (LFPG:KLAX)	2,107,117	2,117,016	9,898	0.47%
Chicago to Hong Kong (KORD:VHHH)	1,774,983	1,829,920	54,936	3.10%
Frankfurt to Los Angeles (EDDF:KLAX)	1,525,221	1,548,293	23,071	1.51%
Heathrow to Calgary (EGLL:CYYC)	396,620	427,704	31,083	7.84%
Frankfurt to Narita (EDDF:RJAA)	2,242,334	2,216,630	-25,704	-1.15%
Heathrow to Seattle (EGLL:KSEA)	696,308	715,710	19,401	2.79%
Kansai to Schiphol (RJBB:EHAM)	1,081,687	1,103,863	22,176	2.05%

5.2.2. Emissions results by airline

The NOx emissions of the modeled flights for the major airlines are presented below. Note that the data in this table correspond to Figure 3-10 in the MITRE Report.

Table 7. NO_x Emissions by airline

Airline	NO_x: Baseline (kg)	NO_x: Alternative (kg)	Difference (Alt – Base) (kg)	Difference (%)
Japan Airlines (JAL)	11,475,940	11,574,324	98,384	0.86%
British Airways (BAW)	11,943,794	12,088,515	144,720	1.21%
Lufthansa (DLH)	11,372,847	11,552,732	179,885	1.58%
United Airlines (UAL)	14,830,102	15,054,228	224,125	1.51%
Air Canada (ACA)	6,701,716	6,897,298	195,582	2.92%
Air France (AFR)	9,152,995	9,105,580	-47,415	-0.52%
KLM	6,725,122	6,825,953	100,831	1.50%
Continental (COA)	7,237,878	7,467,549	229,671	3.17%
All Nippon (ANA)	5,602,994	5,627,296	24,302	0.43%
Korean Air (KAL)	6,723,312	6,810,582	87,270	1.30%
Virgin Atlantic (VIR)	4,247,572	4,261,298	13,726	0.32%
Demodedovo (DMO)	428,058	456,834	28,776	6.72%
America (AAL)	5,315,741	5,407,465	91,724	1.73%
Northwest (NWA)	6,795,763	6,832,686	36,923	0.54%
SAS	2,783,648	2,834,548	50,900	1.83%
Aeroflot (AFL)	949,942	956,122	6,181	0.65%
Yakutia (SYL)	121,632	123,716	2,084	1.71%
Nippon Cargo (NCA)	1,141,858	1,250,005	108,147	9.47%
Cathay Pacific (CPA)	1,175,636	1,203,780	28,144	2.39%
Swiss (SWR)	2,145,116	2,146,221	1,105	0.05%
Zoom (OOM)	278,694	282,347	3,653	1.31%
Delta (DAL)	1,720,347	1,723,664	3,318	0.19%
Air China (CCA)	2,082,517	2,242,109	159,592	7.66%
Cargolux (CLX)	1,035,897	1,062,635	26,738	2.58%
Air Transat (TSC)	368,278	372,162	3,884	1.05%
Finnair (FIN)	1,005,648	1,004,907	-741	-0.07%
Transaero (TSO)	145,248	159,976	14,729	10.14%
Singapore (SIA)	1,186,647	1,184,013	-2,634	-0.22%

5.2.3. Emission results by aircraft type

The NO_x emissions for the modeled flights of the major aircraft types are presented in Table 4 above. Note that the data in this table correspond to Figure 3-11 in the MITRE Report.

Table 8, NO. Emissions by aircraft type

Aircraft Type	NO_x: Baseline (kg)	NO_x: Alternative (kg)	Difference (Alt – Base) (kg)	Difference (%)
B747-4	58,723,436	59,448,536	725,100	1.23%
B777-2ER	28,228,872	28,686,326	457,455	1.62%
A340-3	13,722,776	13,901,266	178,491	1.30%
B767-3ER	4,295,672	4,321,295	25,623	0.60%
A340-6	4,298,266	4,350,300	52,035	1.21%
B777-3ER	6,101,059	6,113,917	12,858	0.21%
A330-2	2,469,899	2,510,015	40,117	1.62%
A330-3	2,640,176	2,720,526	80,350	3.04%
TU154	191,803	195,261	3,459	1.80%
MD11	2,540,520	2,584,974	44,454	1.75%
A340-5	2,867,308	2,908,659	41,351	1.44%
IL62	250,177	270,554	20,376	8.14%
B777-2	2,576,652	2,611,423	34,771	1.35%
B767-2ER	362,320	379,787	17,467	4.82%
IL96	177,094	184,745	7,651	4.32%
B777-3	1,973,829	1,988,546	14,718	0.75%
B747-2	685,773	803,434	117,661	17.16%
B747-4ER	722,268	734,102	11,834	1.64%
A340-2	396,887	399,546	2,660	0.67%
TU204	143,240	144,159	919	0.64%
B737-8	16,382	16,880	498	3.04%
A310-3	30,039	30,667	627	2.09%
B757-2	140,925	140,865	-61	-0.04%
B767-3	196,577	196,809	233	0.12%
B767-2	24,569	25,245	676	2.75%
DC10-3	774,140	774,743	603	0.08%

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