

Global Simulation of Aviation Operations

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The simulation and analysis of global air traffic is limited due to a lack of simulation tools and the difficulty in accessing data sources. This paper provides a global simulation of aviation operations combining flight plans and real air traffic data with historical commercial city-pair aircraft type and schedule data and global atmospheric data. The resulting capability extends the simulation and optimization functions of NASA's Future Air Traffic Management Concept Evaluation Tool (FACET) to global scale. This new capability is used to present results on the evolution of global air traffic patterns from a concentration of traffic inside US, Europe and across the Atlantic Ocean to a more diverse traffic pattern across the globe with accelerated growth in Asia, Australia, Africa and South America. The simulation analyzes seasonal variation in the long-haul wind-optimal traffic patterns in six major regions of the world and provides potential timesavings of wind-optimal routes compared with either great circle routes or current flight-plans if available.

I. Introduction

Global civil aviation is changing from a concentration of air traffic inside US, Europe and across the Atlantic Ocean to a more diverse traffic pattern across the globe with accelerated growth in Asia, Africa and South America¹. The safe and efficient growth of aviation is facilitated by aircraft with similar equipage and aviation procedures that are compatible in different parts of the globe. Further, there is concern about the impact of aviation emissions on health and climate impact²⁻³. Conversely, changes in the weather have an impact on aviation⁴. The ability to deal with these changes requires important investment and policy decisions to be made by aircraft manufacturers, air navigation service providers, airlines and government organizations⁵. Modeling, simulation and analysis are needed at the regional, national and global scales to make informed policy and operational decisions.

There are many simulation and operational tools available to make decisions at the regional and national levels and between some countries⁶⁻⁸. However, there is a dearth of simulation tools at the global level. This paper describes an effort to design and develop a tool to conduct global level analysis of air traffic operations. The tool is an extension of NASA's Future ATM Concepts Evaluation Tool (FACET)⁸, which has been used to conduct several analysis and benefit studies at the national level and is part of a system to make reroute decisions by airlines⁹⁻¹⁰.

Section II describes the components of an US air traffic simulation and the modifications needed to extend it to a global simulation. Section III describes some of the issues and challenges facing the design of a global air traffic simulation. Section IV presents results on the evolution of global traffic during the years 1988-2013 and forecast for the year 2034 to illustrate the basic analysis and display capabilities of the global aviation operations simulation. Section V looks at the impact of winds on long haul flights in different regions and compares the difference between great circle routes and cost-optimal routes. Conclusions and future work are described in Section VI.

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Figure 1. Global air traffic simulation using FACET and analysis tools.

II. US Air Traffic Simulations

There are several modeling tools available for the development of decision support tools and for conducting benefits analysis of air traffic in the US. Air Traffic Management (ATM) makes extensive use of simulations during operations and a review of their fidelity and categorization is available in the literature¹¹. FACET is a simulation and analysis tool developed at NASA to provide a simulation environment for concepts and technology development and evaluation to support future air traffic management systems⁸.

FACET is a flexible simulation environment for exploration, development, and evaluation of advanced Air Traffic Management (ATM) concepts. FACET models en route airspace operations over the contiguous United States and offers ATM researchers a balance of fidelity, flexibility, scalability, and performance. Core features include air traffic simulation, prediction, visualization, and playback of actual traffic data. Four-dimensional aircraft trajectories are modeled using spherical-earth equations. Aircraft are flown along flight plan or great circle routes as they climb, cruise, and descend according to performance models. Performance parameters are obtained from data table lookups or from Eurocontrol's Base of Aircraft Data Revision 3.6 (BADA)¹². Heading and airspeed dynamics are also modeled. The airspace model includes geometric descriptions of Air Route Traffic Control Centers (ARTCCs or "Centers"), their sectors, Victor Airways and Jet Routes, as well as the locations of airports and fixes (navigation aids and airway intersections). Real-time aircraft position and flight plan data are obtained from the Federal Aviation Administration (FAA) Traffic Flow Management System (TFMS). Weather data (winds, temperature, convective cells, etc.) are read and displayed from multiple sources, including the National Oceanic and Atmospheric Administration, MIT Lincoln Laboratories, and the FAA. Fig.1 shows the basic components of the simulation. FACET software integrates three distinct components (1) Data computation using the "C" programming language, (2) display of information through a graphical user interface (GUI) written in Java, and (3) an application program interface (API) using the Java programming language. The FACET API is a set of routines for building software applications to support development of future ATM systems. Many applications generate decision support data and display their results on the GUI.

III. Global Air Traffic Simulation

For the purpose of simulating global aircraft trajectories, the current airspace domain in FACET was modified from US continental airspace to a global scope. Fixes are points in the airspace identified using 3, 4 or 5 letters. An issue that needs to be addressed in developing global air traffic simulations is to be able to resolve common names for different fixes. A database is under development by merging fixes from several countries and by recognizing duplicate names. The computation of aircraft trajectories uses atmospheric data such as wind and temperature provided by the Global Forecast System (GFS)¹³. GFS is a global numerical weather prediction computer model managed by the National Oceanic & Atmospheric Administration with predictions four times a day. Each prediction forecasts up to 16 days in advance, 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.

The worldwide commercial air traffic schedules describing aircraft type, departure time and origin-destination city-pairs are provided by data supplied by OAG Worldwide LLC¹⁴. The simulation uses flight plans from other sources if they are available. The integration of GFS, OAG data, Aircraft data and flight plans enables the simulation of global aircraft trajectories. In this study, global flight schedules are obtained from the OAG. Preliminary records from the OAG data file show that there are 96,682 active flights worldwide with 203 aircraft types flown for

Thursday, June 26, 2014. The top 10 airports worldwide that have the most number of departures and arrivals are listed in Table 1. The ten most frequently flown aircraft types are shown in Table 2. The global flight schedules and aircraft data acquired from OAG are applied for the preparation of simulating global trajectory optimization scenarios with FACET.

Table 1. Ten busiest airports during June 26, 2014.

Rank	Airports	Total Departure and Arrivals	Rank	Airports	Total Departure and Arrivals
1	Chicago (KORD)	2,608	6	Beijing (ZBAA)	1,488
2	Atlanta (KATL)	2,387	7	Charlotte (KCLT)	1,436
3	Dallas (KDFW)	1,936	8	Frankfurt (EDDF)	1,371
4	Los Angeles (KLAX)	1,646	9	Houston (KIAH)	1,370
5	Denver (KDEN)	1,565	10	London (EGLL)	1,338

Table 2. Ten most common aircraft types during June 26, 2014.

Rank	Aircraft Types	Total	Rank	Aircraft Types	Total
1	Airbus A320	14,036	6	Airbus A321	3,764
2	Boeing 737-800	12,252	7	Embraer E-190	2,285
3	Boeing 737-700	6,861	8	Bombardier DH8D	2,222
4	Airbus A319	6,279	9	ATR 72	2,199
5	Bombardier CRJ-900	4,633	10	Embraer ERJ 140	1,974

IV. Evolution of Global Air Traffic Network

The global air traffic simulation was used to generate aircraft trajectories for the same day of the year during the period 1988-2013 to compare how air transportation operations have evolved. The airspace is divided into cells each 1.0×1.0 degree latitude/longitude. The number of aircraft passing through each cell in a day is defined as air traffic density and is an indication of the amount of traffic passing through a particular region in the airspace. Most air traffic is concentrated along the shortest routes between city pairs and only a relatively small amount of worldwide airspace is covered by air traffic. The fraction of cells covered by air traffic is used to measure the distribution and spread of air traffic in the past 25 years. This section presents results to illustrate basic analysis and display capabilities of the global aviation operations simulation. It describes the evolution of global traffic qualitatively and also as a network flow with airports as nodes and the flow between them as links.

Figure 2 shows the global air traffic density for the same weekday, the first Wednesday of June in (a) 1988 and in (b) 2013. The colors in the display depict the air traffic density variation greater than 15. The cells that have density in the range [15-50] are shown in green and those in the range [50-200] are shown in yellow. Similarly, the airspace cells with associated air traffic density greater than 200 are depicted in red. As shown in these figures since 1988, global civil aviation changed from a concentration of traffic inside US, Europe and across the Atlantic Ocean to a more diverse traffic pattern across the globe with accelerated growth in Asia, Australia, Africa and South America.

The blue curve in Figure 3 shows that the percentage of airspace covered by air traffic increased from 33% to 45% during the years 1988-2013. The red curve in Figure 3 shows the increase in air traffic density between 1988 to 2013 for the airspace cells ranked at the top 10 percentile. The figure shows that air traffic not only increased in areas where it was dense in the year 1988, but is spreading to more regions globally.

There are thousands of airports globally and the International Civil Aviation Organization (ICAO) assigns a unique four-letter identification to each of them starting with a letter of the alphabet except the letters I, J and X¹⁵. The ICAO airport codes have a spatial structure with the first letter allocated by continent and represent a country or several countries within that continent. Some large countries like the United States have airports starting with a common letter, K in this case, with the other three letters identifying the airport. The ICAO code for Chicago O'Hare airport and London Heathrow airport is KORD and EGLL respectively. There are some exceptions to the spatial structure due to political or administrative reasons. Figure 4(a) and 4(b) show the variation in traffic inside a region and between different regions of the world during a day in the years 1988 and 2013.

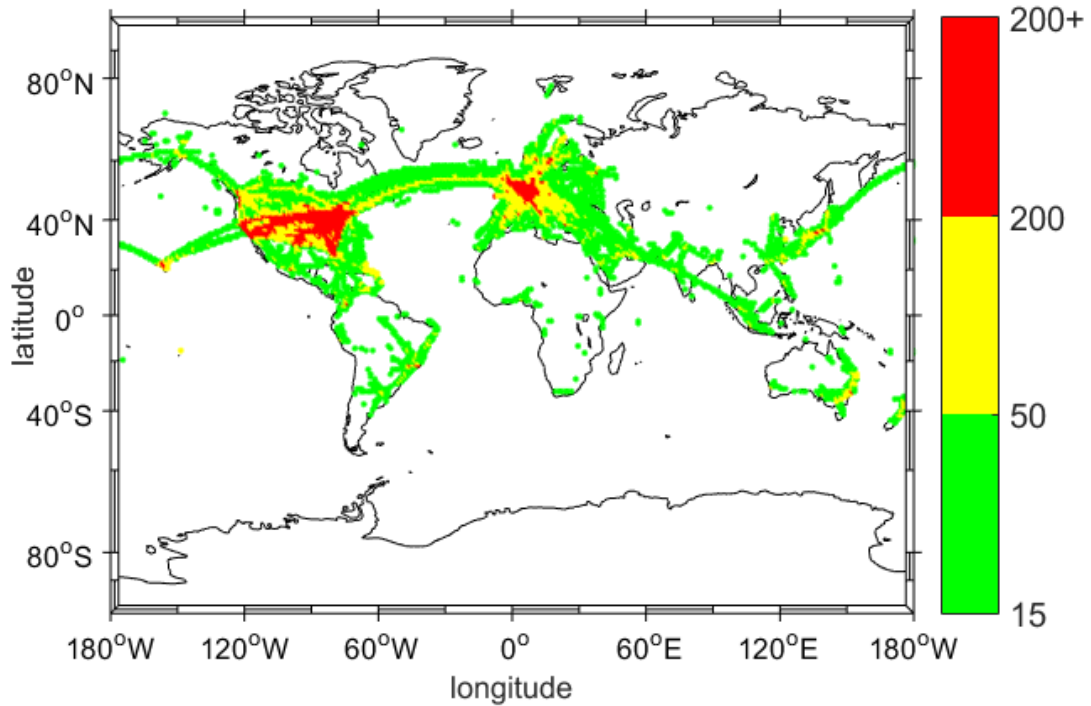


Fig. 2(a): 1988

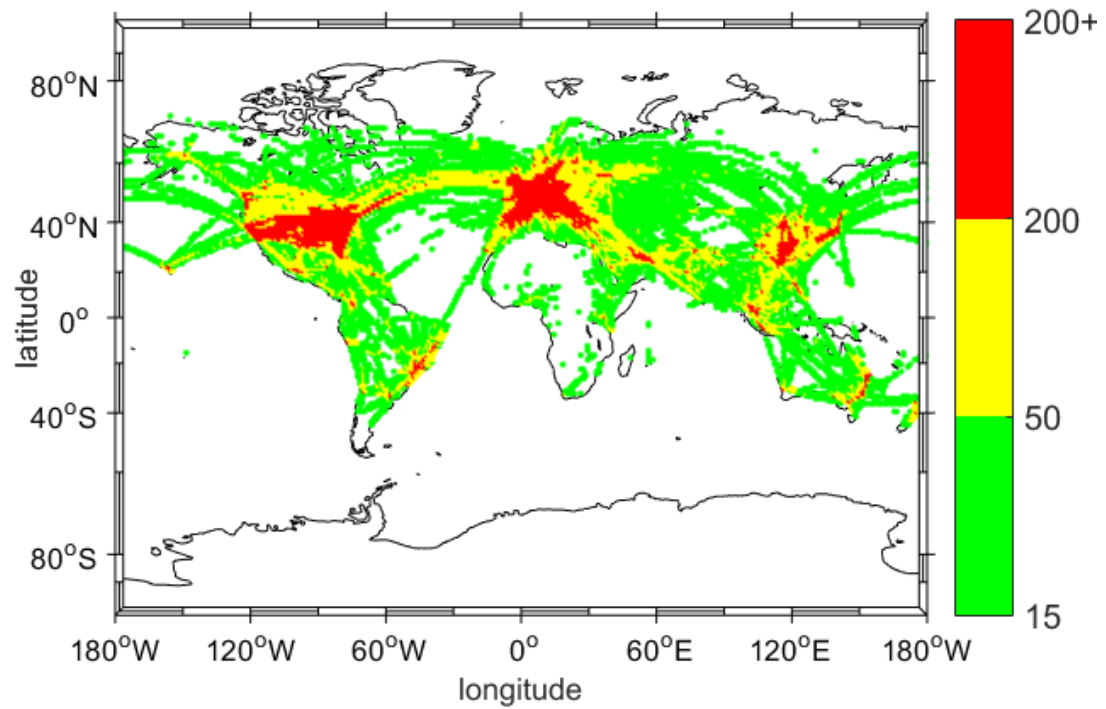


Fig 2(b): 2013

Figure 2. Comparison of global air traffic density during 1998 and 2013.

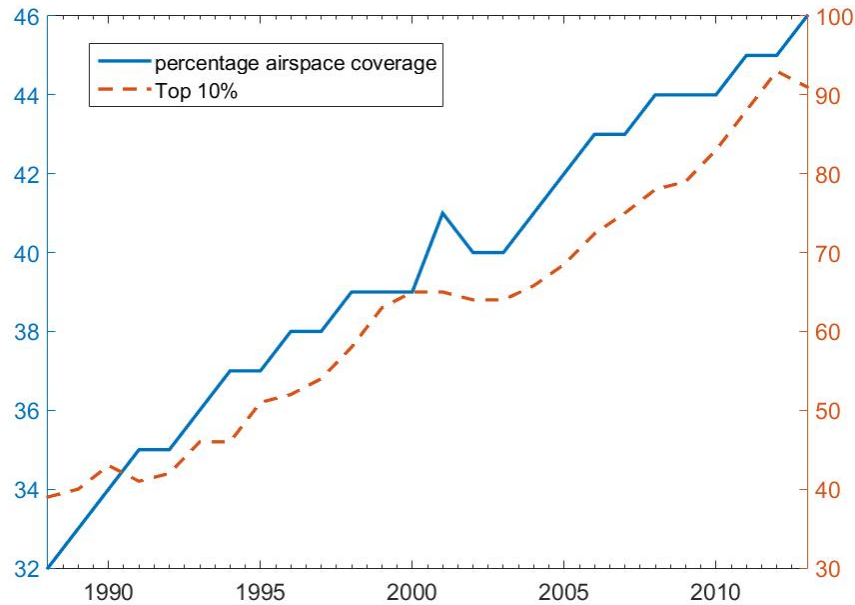


Figure 3. Variation of Global air traffic density during 1988-2013.

The 23x23 matrix in the figures 4(a) and 4(b) shows the traffic flow between airports located in 23 different regions of the world. The alphabets in the figure are grouped geographically and a brief description of airports covered by each letter is provided in the Appendix. The diagonal elements of the matrix indicate air traffic between airports within a region. The off-diagonal elements indicate traffic originating in a region and travelling to an airport in a different region. The different colors are an indication of the number of flights. The number of flights during 1988 was more than 1,000 in seven regions namely United States (K), Canada (C), South America (S), Europe (E, L), Australia (Y) and R (South East Asia). The number of flights between different regions is small with the largest number of inter-regional flights between US and countries in North America and Europe. The increased number of non-zero (colored cells) off-diagonal elements of the matrix in Figure 4(b) shows the shift of aviation from a regional network to a strongly interconnected global network. The number of red diagonal elements has increased from 7 to 14 indicating strong growth of aviation in the Middle East, Russia, China and India.

The 23x23 matrix is aggregated into a 6x6 matrix by grouping airports located in North America (K,C,M,P,T), South America, Europe (E,L,B), Middle East/ Asia (O,U,Z,V), Pacific Ocean Countries (Y,A,N,W,R) and Africa (H,G,D,F). The traffic amongst this aggregated group of airports is shown in Figure 5. The evolution of air traffic network can be captured in a simplified manner, instead of the 30 possible connections, by ignoring connections between the six aggregated regions representing less than 0.2% of the total number of global flights. The numbers in Figure 6 indicate the percentage of total global traffic inside a region. The number near a connecting line indicates the amount of inter-regional traffic expressed as a percentage of the total number of global flights. The blue/red lines and numbers show the network connection in 1988 and 2013 respectively.

The number of flights in the OAG database for the year 1988 is 42,661. North America and Europe provided 75% of the global air traffic in 1988. The inter-regional traffic in 1988 was limited to three major connections between Europe and the regions of North America, Mid-East/Asia and Africa. The number of flights in the OAG database for the year 2013 is 80,190. The share of the North America and Europe in the global traffic reduced from 75% to approximately 60% between 1998 and 2013. There was a significant growth, from 4.6% to 12.2%, in the traffic in the Mid-East/Asia region. The red lines in Figure 5 indicate that there was more inter-regional traffic and more connected regions in 2013.

FAA, Boeing and Airbus forecasted air traffic growth in the next 20 years. The Airbus global market forecast¹⁶ for the years 2015-2034 together with certain additional assumptions were used to predict the evolution of the global air traffic network for the year 2034. The annual growth varies from 1.8% to 7% between inter-regional and intra-regional traffic. The Figure 6 shows the projected global air traffic network for 2034. The notation in Figure 6 is similar to Figure 5. The projected number of daily flights is 190,828. There is significant growth in air traffic in all regions. The total share of North America and Europe in the global air traffic continues to decline to a level of 42%. All other regions show an increase in their share of global traffic with a 4% to 5% increase in Mid-East Asia region.

The forecast model predicts 0.3% of the global traffic between Europe and South America in 2034. There is an increase in the percentage of traffic between different regions in 2034, compared to 2013.

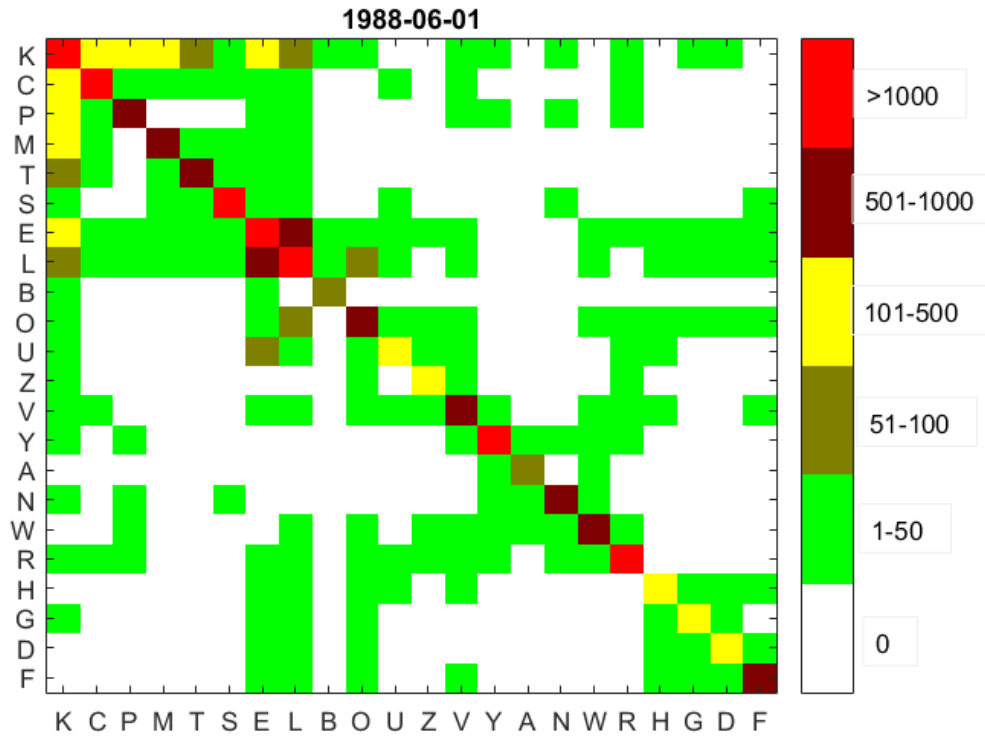


Fig 4(a): 1988

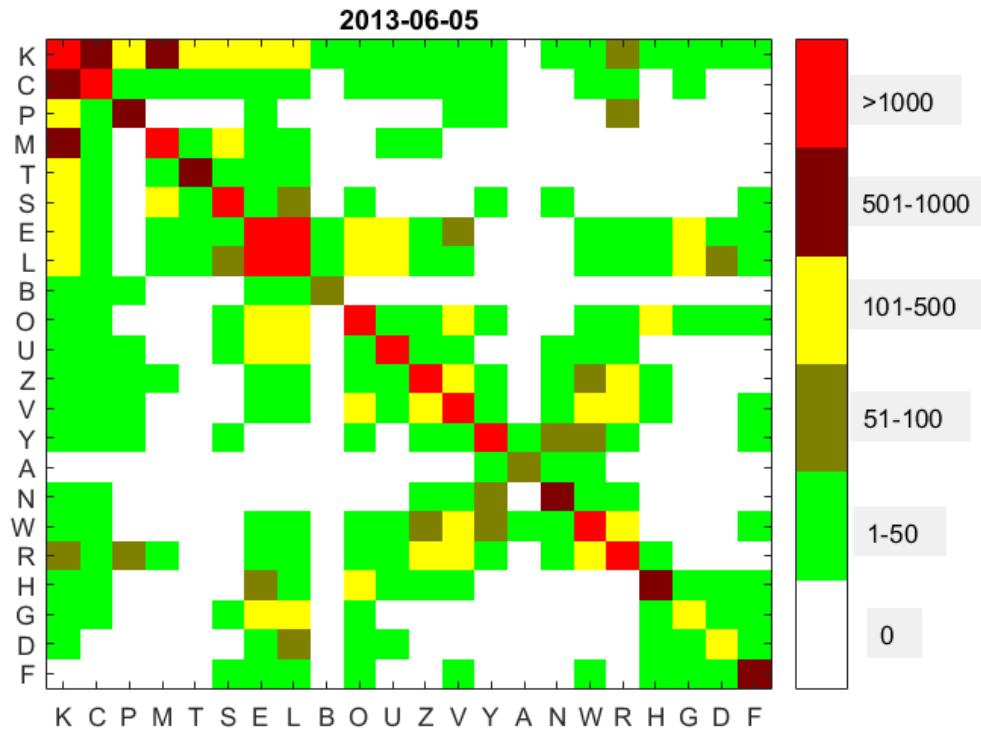


Fig 4(b): 2013

Figure 4. Global distribution of air traffic between 23 regions

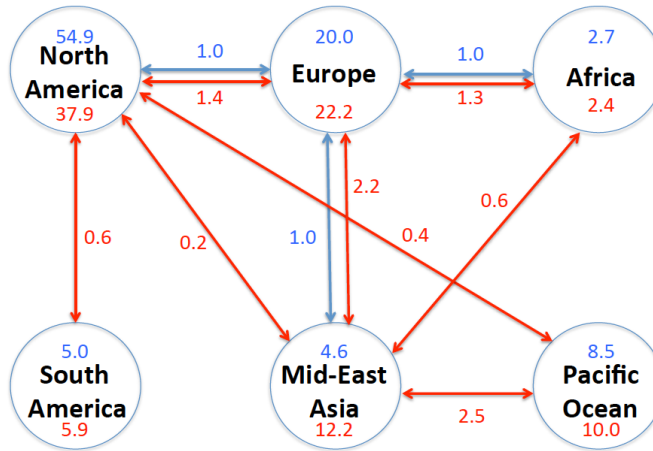


Figure 5. Global air traffic network in 1988 and 2013.

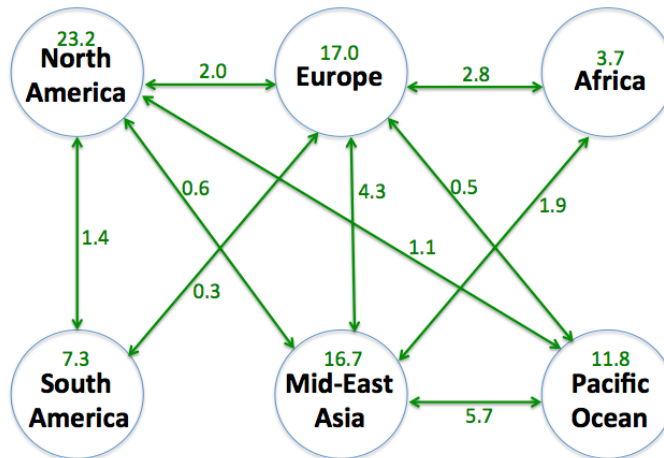


Figure 6. Projected global air traffic network in 2034.

V. Global Wind-optimal Operations

An important application of the Global Air Traffic Simulation is to study the impact of winds on flight path planning in different regions and to compare the difference between cost-optimized aircraft trajectories and great circle routes. A flight planned to follow a great-circle route minimizes its flight distance only and does not minimize the aircraft travel time and fuel burn in the presence of winds. The initial assessment of wind impact is based on potential savings of aircraft travel time resulting from flying wind-optimal routes worldwide when compared with the great-circle routes. The actual route structure is neglected for this assessment to focus only on the impact of winds. In this section, the wind-optimal trajectories and the great-circle trajectories are calculated for global air traffic schedules from OAG and wind data from GFS for the first Wednesday of every month in 2010.

Winds have the most impact on long-haul flights. Long-haul flights are assumed to be aircraft operating between origin/destination airports with great-circle distance longer than 2,000 nmi. Figure 7 shows the numbers of long-haul flights that operated on June 2, 2010 within or between the 6 regions defined in the previous sections. Some of these regions have relatively few flights; Africa (AF) and South America (SA) have less than 50 flights. The largest numbers of long-haul flights are within North America (NA), Mid-East/Asia (MA) and Pacific Ocean (PO) and inter-regional flights between NA, Europe (EU), MA and PO. There are more than 100 daily long-haul flight operations within NA, MA, PO and between the 8 region-pairs PO-MA, MA-PO, EU-MA, MA-EU, EU-NA, NA-EU, NA-PO, and PO-NA.

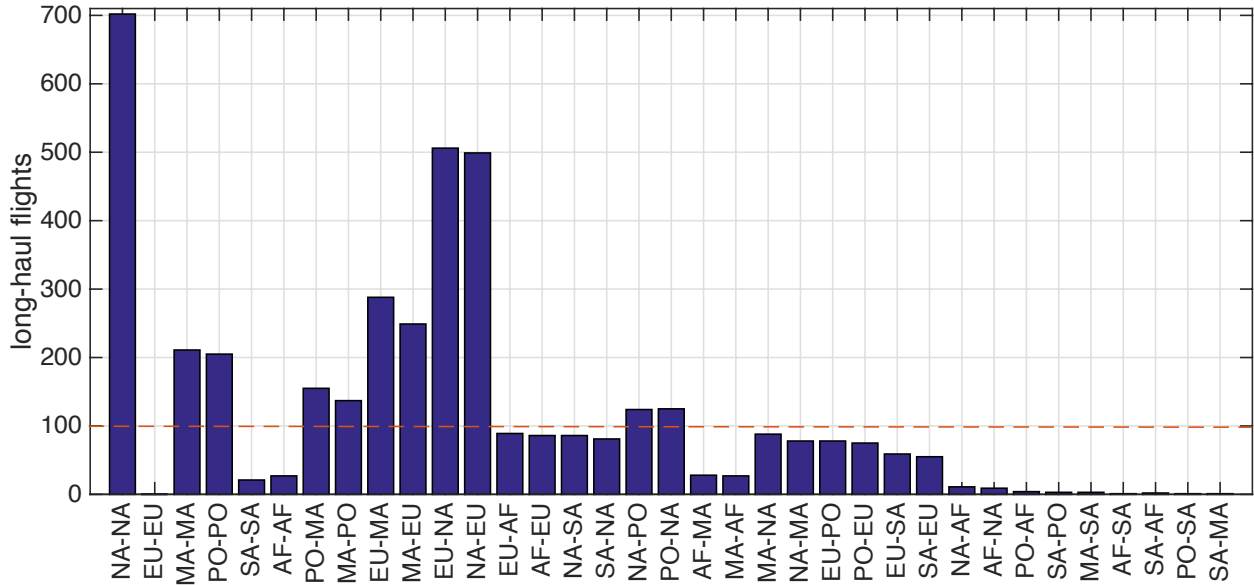


Figure 7. Long-haul flights for 35 origin-destination region pairs during June 2, 2010

Figure 8 plots the number of long-haul flights for each first Wednesday of every month in 2010 for the 11 most frequent region pairs. The number of long-haul flights operating within NA and between NA and EU are the largest. They reach the peak during summer and are the lowest during winter season. The number of long-haul flights operating within MA or PO, and between MA and EU are between 200-300 daily. They are flat except for the intra-regional long-haul flights within MA. Similar to NA and EU regions, they are the lowest during winter. However, they reach the peak between February and March possibly due to the spring festival in Asia¹⁷. The number of daily long-haul flights between NA and PO, and between MA and PO are in the range 100-200.

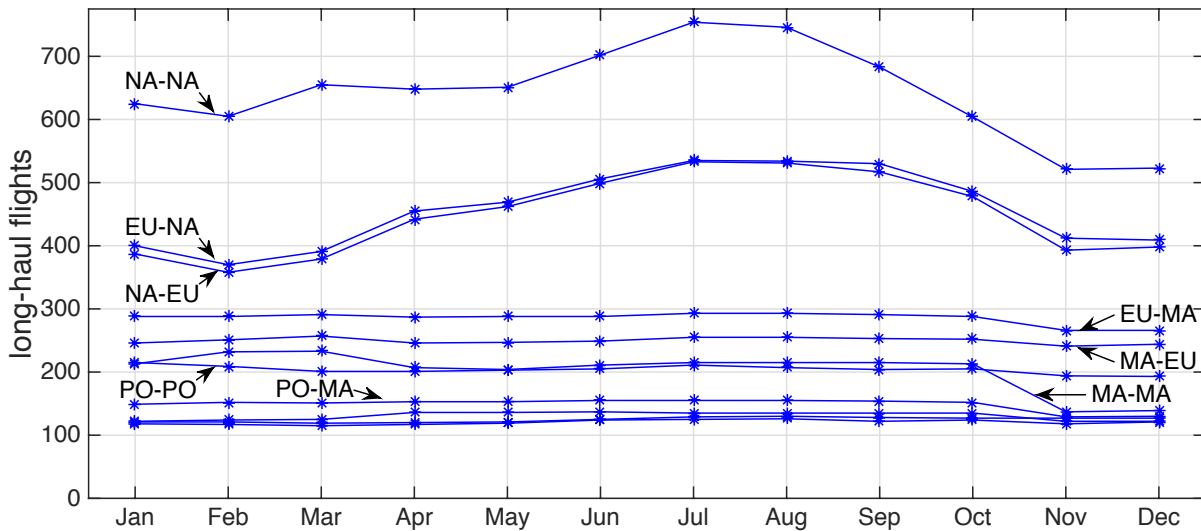


Figure 8. Number of long-haul flights during 2010 for the 11 popular region pairs

The potential time savings resulting from flying wind-optimal routes when compared with the great-circle routes are calculated for the long-haul flights for the 11 region pairs for gaining insight about the impact of wind on long-haul flights. Figure 9 plots the time savings in green for each long-haul flight for the 12 days during 2010 in green asterisk. The mean savings for each region pair is marked by the blue cross and the standard deviation is shown on the upper error bar. The lower error bar is not shown for the cases with negative values. Note that the mean is small due to zero time savings over the great-circle routes for a group of flights in each region pair. For these cases, the

great-circle routes are very close to the wind-optimal routes. Aircraft can minimize travel distance, travel time, and fuel burn by flying the great-circle routes.

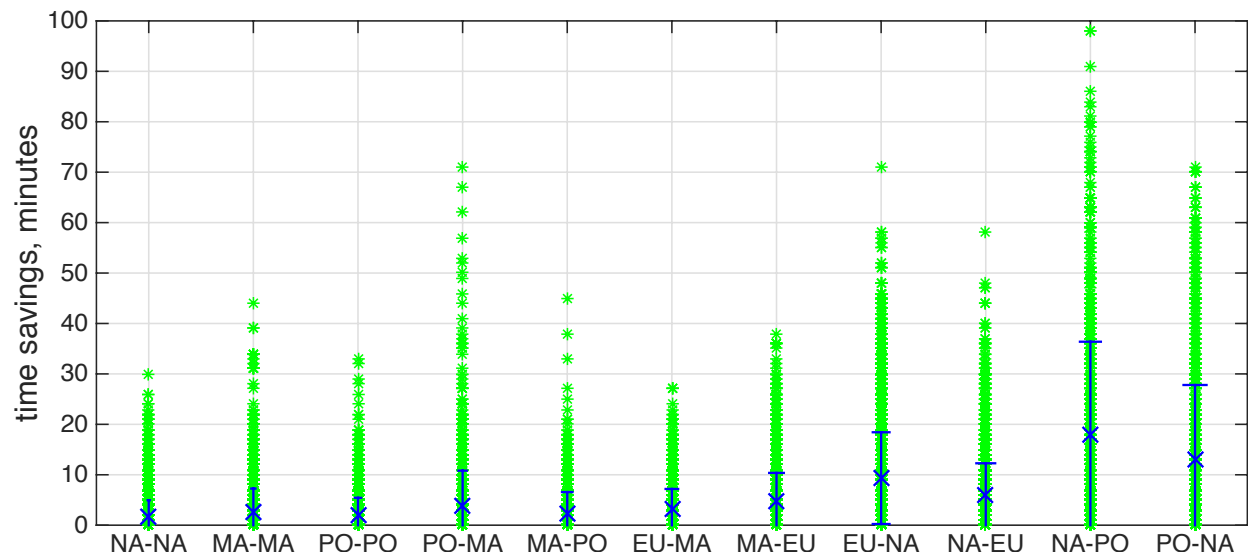


Figure 9. Wind-optimal time savings over great-circle routes for 11 popular region pairs during 2010

Table 3 presents the total number of flights for each region pair and the number of flights compared to great circle route with time savings more than one minute, 5 minutes, and 10 minutes, respectively, along the wind-optimal routes.

Table 3. Total number of flights and flights with positive time savings.

Region Pairs	NA-NA	MA-MA	PO-PO	PO-MA	MA-PO	EU-MA	MA-EU	EU-NA	NA-EU	NA-PO	PO-NA
No. Flights	7,717	2,434	2,448	1,788	1,564	3,427	3,996	5,497	5,377	1,446	1,495
Savings > 0 min	3,667	1,194	1,206	991	760	2,098	2,166	4,845	4,471	1,119	1,191
Savings > 5 min	624	322	294	393	221	741	900	3,037	2,021	839	819
Savings >10 min	157	146	75	173	101	219	420	1,772	992	632	588

Long-haul flights along the wind-optimal routes between NA and PO have the largest timesaving on average. The mean savings are around 10-20 minutes and 17% of flights saved more than 30 minutes due to strong jet stream in the oceanic airspace. For the same reason, transatlantic flights between NA and EU and oceanic flights between PO and MA have the second largest timesavings. Long-haul flights between MA and EU have the relatively smaller savings among all inter-regional flights. Note that westbound long-haul flights from NA to PO, EU to NA, PO to MA, and MA to EU have a larger time savings then the associated eastbound flights. In general, westbound air traffic operates in the presence of head winds has a higher time penalty for deviation from wind-optimal path. Due to longer distances, the potential timesavings for the inter-regional flights are larger than those operating within their regions.

Based on OAG, there are 4,115 westbound flights from EU to United States (US) and 4,012 eastbound flights from US to EU during the 12 days in the year 2010. The mean timesavings based on a comparison between wind-optimal routes and great-circle routes is 1.9% for the westbound flights and 1.4% for the eastbound flights over this period. An earlier study¹⁸ analyzed and compared actual flight routes to their wind-optimal counterparts for transatlantic flights between US and EU. The range of potential savings for the 100 busiest city pairs that have the most transatlantic flight operations is between 10.6% and 1.5% for the eastbound traffic and between 5.8% and 1.4% for the westbound traffic respectively. In general, the potential savings from actual flight routes are higher than those based on great-circle routes due to limitations of actual track structure and additional real-time air traffic constraints accounted during flight planning. Generally, savings for the eastbound traffic is higher than those for westbound traffic implying that westbound flight operations are closer to wind-optimal routes.

These results provide an insight to the impact of wind on flight path planning. Currently, Pacific Organized

Track System and North Atlantic Track System (NATS) are designed to align airways with jet streams in the oceanic airspaces for transpacific and transatlantic air traffic. The oceanic tracks are updated daily to accommodate latest weather forecasts for enhancement of air traffic efficiency and reduction of aircraft fuel burns and emissions. As presented in the previous section, the forecast of air traffic growth in the next 20 years shows an increase in their share of global traffic with a 4% to 5% increase in the MA region. Oceanic track systems similar to NATS can be designed for traffic between MA and PO, and between MA and EU to accommodate the traffic growth in these regions.

In addition, the long-haul flights amongst the aggregated group of airport pairs with large time savings demand higher priorities during strategic planning for both airlines and the air traffic management system due to higher time and fuel penalties for deviation from the wind-optimal path. The potential fuel burn saved by these flights also depend on the aircraft types operating in the fleet and varies with weather conditions. A database can be built using the wind-optimal routes based on historical wind conditions and past air traffic data for development and enhancement of track structure for worldwide air traffic.

VI. Conclusions and Future Work

This paper describes the components of an US air traffic simulation and the modifications needed to extend it to a global simulation. It describes some of the issues and challenges facing a global air traffic simulation. The paper illustrates the basic analysis and display capabilities of the global aviation operations simulation.

The simulation was used to characterize the evolution of global air traffic during the period 1988-2013. During this period global civil aviation changed from a concentration of traffic inside US, Europe and across the Atlantic Ocean to a more diverse traffic pattern across the globe with accelerated growth in Asia, Australia, Africa and South America. The total number of commercial flights doubled during this period. The share of the North American and European air traffic in the global traffic reduced from 75% to approximately 60% between 1988 and 2013. The inter-regional traffic in 1988 was limited to three major connections between Europe and the regions of North America, Mid-East/Asia and Africa. There was a significant growth, from 4.6% to 12.2%, in the traffic in the Mid-East/Asia region.

Global air traffic is predicted to grow at annual rates varying from 1.8% to 7% between inter-regional and intra-regional traffic during the next 20 years. This will lead to flights between city-pairs more than twice today's levels. As in the last twenty years, the total share of North American and European air traffic in the global air traffic is projected to decline to a level of 42%. All other regions show an increase in their share of global traffic with a 4% to 5% increase in the Mid-East Asia region.

An important application of the Global Air Traffic Simulation is to study the impact of winds on flight path planning in different regions and to compare the difference between cost-optimized aircraft trajectories and great circle routes. The initial assessment of wind impact is based on potential savings of aircraft travel time resulting from flying wind-optimal routes worldwide when compared with the great-circle routes.

Long-haul flights along the wind-optimal routes between the North America and the Pacific Ocean regions have the largest timesavings on average. The mean savings are around 10-20 minutes with 17% of flights saving more than 30 minutes due to the strong jet stream in the oceanic airspace. For the same reason, transatlantic flights between North America and Europe and oceanic flights between Pacific Ocean region and Mid-East/Asia region have the second largest timesavings. Long-haul flights between Mid-East/Asia and Europe have relatively smaller savings among all inter-regional flights. In general, westbound air traffic operating in the presence of head winds has a higher time penalty for deviation from a wind-optimal path.

The simulation can be used to evaluate the impact of different operational policies to reduce the impact of aviation on climate³ and the impact of climate on aviation⁴. The simulation can be used expand the previously developed integrated capability¹⁸ combining traffic flow management concepts with both CO₂ and non-CO₂ emissions. It will enable evaluation of global operational strategies for minimizing aviation impacts on climate change by flying wind-optimal routes while avoiding regions of persistent contrails formation.

Appendix

This appendix is provided as an easy reference to locate airports with ICAO designation¹⁶.

First Letter	Country/Region	First Letter	Country/Region
A	Western South Pacific	N	South Pacific
B	Greenland, Iceland, and Kosovo	O	Pakistan, Afghanistan and Western Asia
C	Canada	P	Alaska, Eastern North Pacific
D	Eastern West Africa	R	Taiwan, Korea, Japan
E	Northern Europe	S	South America
F	Central and Southern Africa	T	Eastern and Southern Caribbean
G	Western Africa	U	Russia, Georgia, Ukraine
H	East and Northeast Africa	V	India and South Asia
K	US (Lower 49 States)	W	Indonesia, Malaysia
L	Southern Europe, Turkey	Y	Australia
M	Central America, Mexico	Z	China, Mongolia

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