Design of a Flight Planning System to Reduce Persistent Contrail Formation to Reduce Greenhouse Effects

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Abstract*- During flight, aircraft emit greenhouse gases as well as water vapor and other byproducts. When water vapor combines with soot and other particulate matter, condensation trails (contrails) can form and persist in Ice Supersatured Regions (ISSR). Analysis of 45 days of varying atmospheric configurations showed that the location of ISSR can vary between Flight Level (FL) 267 to Flight Level 414, and are most prevalent in the summer months. This paper describes the design of a decision support system to assist in the flight planning of short, medium, and transcontinental routes to avoid the ISSR. The decision support system includes two independent input variables and five output dependent variables. Based on the length of the flight, and the amount of ISSR avoidance, the system can present a tradeoff analysis between (i) the miles of contrails formed, (ii) the amount of fuel consumed, (iii) the time spent in air, (iv) the distance traveled, and (v) the amount of CO2 produced. Results for a normal day's flight schedule for 45 days of ISSR configurations shows that the airline flight routes provide both warming and cooling radiative heating effects that are sensitive to the meteorological conditions and time of day (i.e. solar azimuth). Over the course of long flights, ISSR avoidance caused the aircraft to fly about two percent further; while contrail avoidance on short flights caused up to five percent or more increase in distance. Based on the analysis using the system, it is recommended that all flights over stage length of 1,000 nm be required to avoid ISSR because the radiative forcing due to contrails is tends to be greater than the radiative forcing caused by excess CO2 emissions to avoid contrail regions.

Index Terms- aviation, contrail, flightplanning, greenhouse, radiative forcing

INTRODUCTION

Global Climate Problem

The World Health Organization (WHO) projects the world population reaching to 10 billion humans by the year 2100 [1]. With an increasing world population, the global energy demand will increase causing the increased burning of fossil fuels. Fossil fuels, when burned, produce greenhouse gases, such as carbon dioxide, that can stay in the atmosphere for centuries and cause higher global temperatures. Figure 1 summarizes the aforementioned information.

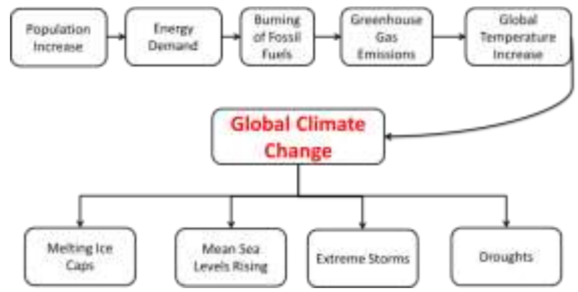

FIGURE 1

Air Travel Demand

With an increase of air travel in the United States, there has been more attention drawn to the environmental impact on the use of aircraft in the National Airspace System. The demand in 1996 was for 7,289,449 flights per year. By 2012, there was a demand for 8,441,999 flights - indicating more than a 15% increase in the demand for air travel from 1996. Additionally, with an increased in demand, there has also been an increase in the amount of fuel consumed by aircraft. From 1977 to 2012, there has been an increase of over 26% for the amount of fuel that aircraft use [2].

Air Traffic Control

The Federal Aviation Administration has designated Federal Airways (FARs) that are decomposed into 2 categories: Very High Frequency (VHF) Omnidirectional Range (VOR), and Colored Airways. The latter is only used in Canada, Alaska, and coastal areas. VORs are predominately used within the continental United States and were established in 1950's for aviation navigation [3].

Aircraft Emissions

The process of the combustion of jet fuel produces carbon dioxide, sulfur oxides, soot, hydrocarbons, and nitrogen oxides. Estimates show that aviation is responsible for 13% of transportation-related fossil fuel consumption and 2% of all anthropogenic CO2 emissions. The transportation industry as an entirety is responsible for 28% of CO2 emissions in the United States [4].

Contrails

Persistent contrails form cirrus clouds made of water vapor from engine exhaust that freezes, forming ice particles upon contact with the free air, leading to visible contrail formation that can last up to 2.7 hours and span about 400 kilometers formed in ice supersaturated regions (ISSR) in the upper troposphere's regions relative humidity levels greater than 100% and temperatures below -40 degrees Celsius [5]. In 1992, linear contrails were estimated to cover about 0.1% of the Earth's surface, and the contrail cover was projected to grow to 0.5% by 2050. Recent reports state that persistent contrails may have a three to four times greater effect on the climate than carbon dioxide emissions in a time horizon of 20 years [6].

Analysis of 45 days of varying atmospheric configurations from the National Oceanic and Atmospheric Administration's Rapid Update Cycle database showed that the location of ISSR can vary between FL 267 to FL 414, and are most prevalent in the summer months. ISSR also appears to be more likely in lower altitudes from September to April, as depicted in Figure 2.

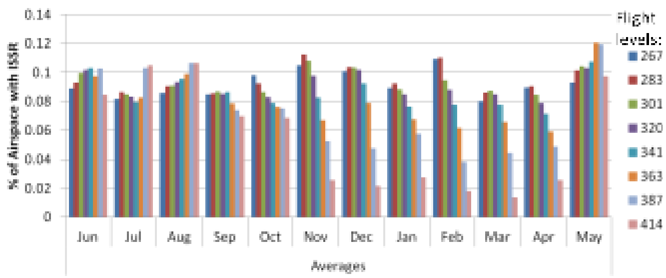

FIGURE 2

Radiative Forcing

Radiative forcing (RF) is a measurement of the energy per area (measured in W/m^2) that is dependent upon shortwave radiation from the sun (R_{SW}) and outgoing longwave radiation from the earth (R_{LW}). The interaction of R_{LW} and R_{SW} with contrails creates a net heating effect on the earth, dependent upon the solar azimuth in a given diurnal cycle.

Figure 3 displays the net warming effects that aviation has on the earth in terms of radiative forcing. From this Government Accountability Office document, it can be noted that contrails have a net radiative forcing affect that exceeds the effects of carbon dioxide. Furthermore, because contrails can induce cirrus cloud formation, when discussing the RF effects of contrails, RF from cirrus cloud formation is traditionally grouped with contrail RF. It must also be noted that the scientific knowledge behind contrails is still in its infancy- contrail parameters such as opacity and optical density require further research [7].

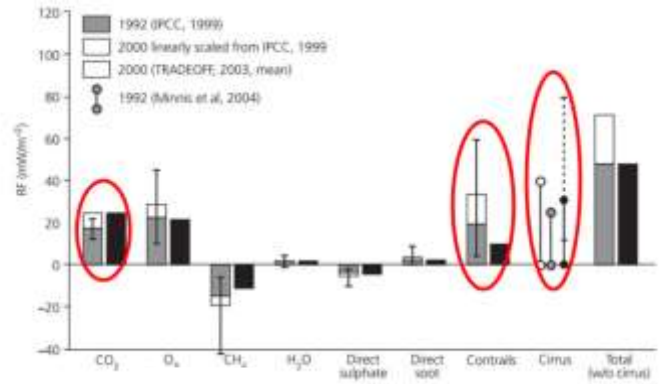

FIGURE 3 [7]

STAKEHOLDER ANALYSIS FOR PRIMARY STAKEHOLDERS

If a system is used to avoid the RF effects of contrails, stakeholders such as the Federal Aviation Administration (more specifically the Air Traffic Organization department), airline management for airlines utilizing the National Air Space (NAS), the consumers of air travel, and other citizens concerned about climate change become important to consider in the decision-making process.

Congress

Congressional representatives are elected to express their constituents' desires and concerns in the lawmaking process. It is in the best interest of representatives in the United States legislature to express their voters' key interests in the policy-making arena, considering that the voters have the opportunity to vote out the representatives if they feel their views are not being properly expressed.

The legislation passed through congress impacts federal administrative bodies such as the United States Department of Transportation (DOT) and agencies under the DOT, such as the Federal Aviation Administration. Furthermore, Congress also determines budgets for the administrative bodies to carry out their tasks.

Federal Aviation Administration- Air Traffic Organization

Under the umbrella of the Department of Transportation, the Federal Aviation Administration (FAA) designates the Air Traffic Organization (ATO) to ensure the safe and efficient transportation in the increasing density of the National Airspace System (NAS) [3].

Airlines-Airline Management

Although it is in the best interest of an airline to provide users (customers) with safe transportation, airlines exist primarily to make a profit. Their main concern is to provide customers with faster flight times at lower operational and fuel costs. At the same time, for the continuity of operation, airlines are subjected to regulations set forth by the FAA.

Citizens and Climate Change Advocates

Because the effects of condensation trails exist mainly on a regional level, citizens and climate change advocates may be concerned about the net heating conditions in their particular areas contributing to global warming.

Stakeholder Tensions

The primary goal of the Air Traffic Organization is to maintain a predetermined level of safety for the successful air travel operations within the National Airspace System. The airline management's main goal is to maintain financial viability while satisfying user demand. Additionally, customers (citizens/public/environmental advocates) demand safe transportation, with minimal monetary costs for air travel, as well as a clean natural environment.

Win-Win Situation

The discussion of a win-win situation is motivated by the simple fact that the National Airspace System (NAS), a free resource, has been overused; thereby not allowing the Earth's natural processes to handle the pollution.

A possible scenario in which the primary stakeholders can be satisfied involves the general public to push concerns on to Congress to create legislation supporting initiatives to reduce aviation's impact on the environment. Legislation can be enacted to regulate standards for more efficient engines, airframes, as well as operational standards. Part of this legislation can include an incentive program for participating airlines obtaining tax credits, thereby increasing airline revenue. Participation can also involve a requirement for airlines to invest in greener technologies, thereby possibly increasing jobs. The general public would have a cleaner environment, and as a result of goodwill, may re-elect legislators.

PROBLEM AND NEED STATEMENTS

Gap Analysis

There are three major driving factors that can have significant impact on the contrail coverage in the sky. The first driving factor is the number of aircraft demand in the sky (at cruise altitude). In addition to the air traffic density, the quantity and types of engines being used may have a significant consequence on the coverage of contrails. The third driving force for contrail coverage is regarding the temperature and humidity conditions existing in the cruising altitude.

Keeping these driving factors in mind, it has been determined that the goal of the project is to reduce the radiative forcing due to contrails to 7.06 mW/m^2 as depicted in Figure 4. The logic behind this gap analysis follows from the International Air Transport Association's pledge to reduce carbon emissions to obtain carbon neutrality by 2020 to a baseline level of 2005 [4].

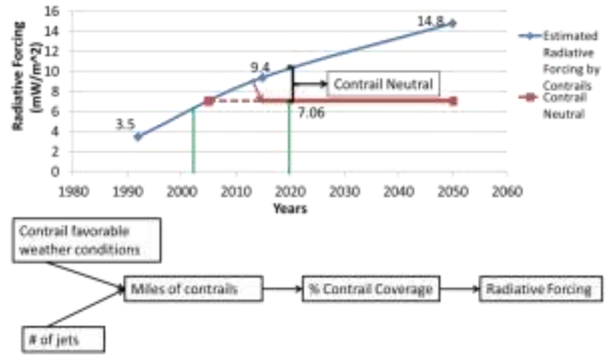

FIGURE 4

With an increase in the demand for air travel resulting in the environmental impacts discussed in the Context Analysis, there is also a need for determining flight paths to reduce the amount of persistent contrails that can form. Currently there is no existing system that provides flight paths for aircraft to avoid Ice Supersaturated Regions (ISSR) while accounting for the tradeoffs between fuel consumption, the amount of time aircraft are in the air, as well as the miles of contrails that are formed by ISSR avoidance flight plans.

Need Statement

In order to solve the problem of radiative heating due to contrails, the ultimate goal of the project is to design a system for the airline dispatcher to create a flight plan that reduces persistent contrail formation while taking into consideration the tradeoffs between fuel consumption, the amount of time aircraft are in the air, as well as the miles of contrails that are formed by ISSR avoidance flight plans.

DESIGN ALTERNATIVES

The goal of the system is to provide a strategic flight plan for each individual commercial jet flight. The input of the system is the integration of the Rapid Update Cycle (RUC) weather system developed by the National Oceanic & Atmospheric Administration (NOAA) and historical flight paths obtained from the FAA's Enhanced Traffic Management System (ETMS). The flight path computation for the aircraft involves using humidity and temperature provided by the RAP database to calculate areas with a relative humidity with respect to ice (RHi) that is greater than or equal to 100% [8]. The system will also perform a tradeoff between creating a flight path, the fuel consumption, as well as the amount of emissions in the creation of an optimal flight path.

Contrail Avoidance Heuristics

An array of heuristic values (0, 100, 1000) was applied to all flights to create different aggressiveness of ISSR avoidance levels. The 0 avoidance heuristic represents no avoidance (GCD), and 1000 heuristic represents total ISSR avoidance, or as much as possible. The system then generated a flight path for each flight heuristic, and weather data set combination.

Categorization of Flights based on Distances

These partial avoidance alternatives are analyzed for flights that are short distance, medium distance, and long distance. The distances are further defined in Table I.

Flight Distances	
Short Distance (S)	< 500 nm
Medium Distance (M)	500-999 nm
Long Distance (L)	>1000 nm

TABLE I

Combining the contrail avoidance heuristics and the flight distances at which the avoidance is being attempted results in 9 possible alternatives. In each row of Table I, the numerical value (0, 100, 1000) represents the contrail avoidance heuristic, and the letter value (S, M, L) represents the flight type, by distance.

GCD Route

The first route considered by the system is the great circle route. This route is the most optimal for the aircraft to fly without taking any avoidance measures into account. The flight path is routed along the shortest route possible between the two airports which results in a straight line. These routes are determined by the 0 avoidance heuristic.

Comparing Alternatives

The best anticipated alternative flight path is a path that consumes the least amount of fuel, has the shortest flight duration, and makes the least miles of contrails. Aircraft spacing safety is an important value for the system; however, safety will be handled externally by air traffic control and not the system.

DESIGN OF EXPERIMENT

Scope

The experiment was scoped to the Continental United States (CONUS), and took into account commercial jet aircraft at cruising altitudes. The specific flight levels taken into account in this system are 267, 283, 301, 320, 341, 363, 387, and 414. The reason of scoping to only 8 flight levels is based on the availability of data. Lastly, radiative forcing was calculated only through deterministic quantities because of the lack of data available to create a stochastic environment.

NOAA RUC Database

The National Oceanic and Atmospheric Administration (NOAA)'s Rapid Update Cycle (RUC) database was utilized for this analysis. 45 different days of weather data from NOAA's RUC database were used to represent a small sample of atmospheric configurations. The weather information included Temperature data, Relative Humidity with respect to water, as well as a multitude of other variables. All of the weather information was encoded into cells of 13.54x13.54 kilometers on a Lambert Conformal Conic map projection. All the data presented in the grid was in units of kilometers from a reference point; therefore, a tool was created to determine latitude and longitude values.

FAA ETMS Database

A sample of 400 flights on one day was randomly selected from the FAA's Enhanced Traffic Management System (ETMS) database. The quantity of flights for this experiment was constrained by the computational resources available to run the simulation. Additionally, the sample of 400 flights was subdivided into categories of long, medium, and short distance flights. Each category contained a representative sample of flights representative of the day of flight data available to use. Therefore, 39% of the flights were short distance, 20% were medium distance, and 42% of the flights were long distance.

ISSR Avoidance

SIMULATION

Figure 5 shows the various inputs and outputs to and from the simulation.

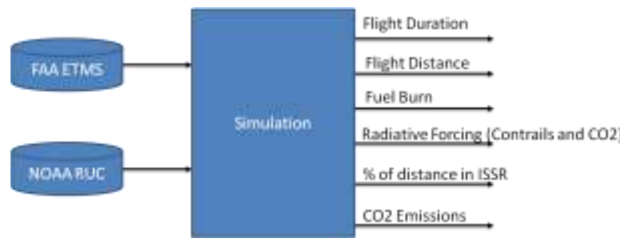

FIGURE 5

System Inputs

The decision support system for planning flight paths around ice supersaturated regions has the following inputs.

1) Weather grid for actual weather from 45 days

The current weather grid is obtained from NOAA's Rapid Update Cycle database. Every hour, NOAA outputs a .grib2 file that can be converted to a csv and then input into the simulation. Specifically, the Relative Humidity with respect to water (RHw) is combined with Temperature (T) data from the .grib2 file to create another grid with Ice Supersaturated Regions. The following model, known as the Schmidt-Appleman criterion, represents RHw and T combining as a function of Relative Humidity with respect to ice (RHi):

$$RHi = RHw\frac{6.0612e^{18.102T/(249.52+T)}}{6.1162e^{22.577T/(273.78+T)}} \quad (1)$$

If the region will produce a contrail, (RHi > 100%), then the grid is marked with the value of 1. If the region would not produce a contrail, relative humidity with respect to ice of less than 100%, then the region is marked with a 0.

2) Aircraft Type (i.e. B737)

The type of aircraft flying is gathered from the FAA's Enhanced Traffic Management System (ETMS). The type of aircraft and various information specific to the aircraft from the can be input into aircraft physical models with Eurocontrol's Base of Aircraft Data (BADA) coefficients to calculate time in flight, fuel use, and CO2 produced by the aircraft over the course of the flight. The following model represents aircraft rate of fuel burn where H_p represents the altitude, V_{TAS} represents true airspeed, and C_x represent BADA coefficients.

$$f_{cr} = \left[C_{f1}\left(1+\frac{V_{TAS}}{C_{f2}}\right)\right]\left[C_{TCR} * C_{TC,1}\left(1-\frac{H_p}{C_{TC,2}}+C_{TC,3} * H_p{}^2\right)\right][C_{fcr}] \quad (2)$$

Once the fuel consumption is multiplied by time in air, CO2 emissions can be calculated in kilograms, using (3),

$$CO_2\ Emission = f * c \quad (3)$$

where *f* is the fuel in kilograms, and *c* is a constant equal to 3.175.

3) Flight Plan Data

Using ETMS tracking data, the origin, destination, and 1-minute updates on aircraft location can be determined. More specifically, for this system, the ETMS data will only be considered for determining where an aircraft enters into cruising altitude and where it leaves cruising altitude. Furthermore, the 1-minute updates on location will be used to determine V_{TAS} and the latitude and longitude information of the aircraft. The 1-minute updates will also be used to determine the flight level at which the aircraft is flying.

4) Contrail Avoidance Algorithm

The A* flight path algorithm is used to determine the shortest path between the start and ending cell in the grid and determines how much contrail avoidance is attempted.

System Outputs

The decision support system for planning flight paths around ice supersaturated regions has the following outputs.

1) Distance Flown

The distance flown by the aircraft in the simulation is calculated for the flight path attempted. The time that the aircraft is in the air can be calculated based off of the distance and speed for the specific aircraft type following the flight path using the following model:

$$time = \frac{distance}{V_{TAS}} \quad (4)$$

2) Distance of Contrails Produced

The distance of contrails produced is calculated based off of the number of cells within the weather grid that the flight path encounters with the value of 1. The value of "1" means that the region is an ISSR, and will produce a contrail when the aircraft flies through it. Based on the size of the cell (13.54 km), the distance of the contrail can be calculated.

3) Fuel Burn

Fuel burn is calculated based off of the type of aircraft and distance flown. Given an aircraft type the system is able to gather the aircraft parameters from the BADA aircraft database. These values can then be used with the distance to calculate the total fuel that the aircraft uses during flight.

4) Kilograms CO2 Produced

The amount of CO2 produced can then be calculated based off of the aircraft type and the amount of fuel burned. This is a simple first order calculation expressed in the "Aircraft Type" section.

5) Radiative Forcing

The radiative forcing can be estimated based off of a first order estimation. The length of the contrails is calculated from the flight path; however, the width of the contrails is held at a constant width of one third of a cell on the weather grid (4.513 kilometers). This is due to average contrail width calculations done by previous studies. The system will output radiative forcing caused by CO2 and contrails.

The following model represents radiative forcing by contrails, where $RF_{nets}(t,s)$ is a sum of radiative forcing by longwave and shortwave radiation, and $W(t,s)$ is the width of the contrails. t is a time parameter for the contrails, and A_{Earth} represents the surface area of the earth.

$$RF_{net}(t) = \frac{1}{A_{Earth}}\sum_{flights}\int RF_{nets}(t,s)W(t,s)ds \quad (5)$$

To calculate the radiative forcing due to carbon dioxide, the facts that about 641 Tg of CO2 are produced per year, and that CO2 has a 0.03 W/m^2 RF impact on the global environment. Excess CO2 emissions resulting from contrail avoidance routes were determined as a percentage of total CO2 emissions. The resulting percentage was multiplied by 0.03 W/m^2 to determine the RF by CO2 for each flight path [9].

RESULTS

A representative sample of 400 flights on a standard day of flight schedules was simulated for 45 days of ISSR. The results display that with more aggressive avoidance maneuvering (higher heuristic values), the aircraft travels a larger distance; thereby increasing the distance flown, kilometers of contrails formed, the flight duration, and the fuel consumption. Figure 6 displays that as the avoidance heuristic increased for longer flights (x-axis), the aircraft flew through more cells in the grid (red), creating for longer flight paths; however, it traversed less ISSR cells (blue).

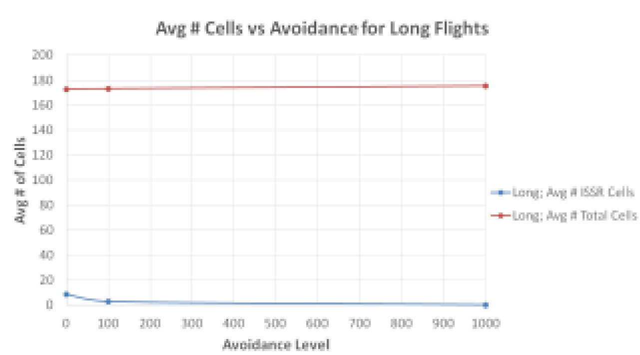

FIGURE 6

It was also noted that for short distance flights, the change between GCD and 1000 avoidance resulted in about a 5% increase in distance on average. For medium and long distance flights the change between GCD and 1000 avoidance resulted in about 2% increases in distance. Furthermore, for short flights, from GCD to 1000 avoidance, the distance in ISSR decreased by 81% on average per flight, whereas the distance in ISSR decreased by 98% per flight on average. Lastly, with 0 avoidance, on average, the shorter flights spent about 8% of their flight in ISSR cells, whereas longer flights spent only about 4%. With 1000 avoidance, these values changed from 2% to 0.1%, respectively. Figure 8 displays a frequency count of additional distances that aircraft had to cover with

Results further displayed that regardless the amount of avoidance, the radiative forcing caused by traversing ISSR exceeded the radiative forcing caused by additional CO2 emissions. Figure 7 displays that for long flights, although avoidance is increasing on the horizontal axis, the radiative forcing due to contrails is always higher than radiative forcing by CO2.

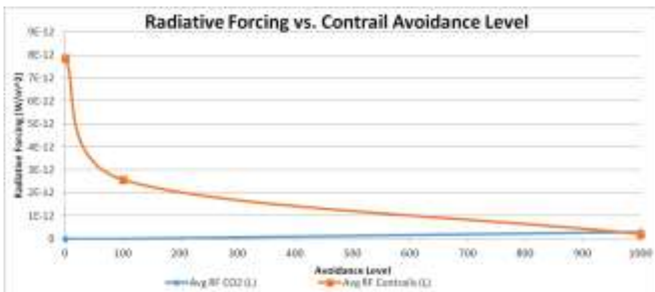

FIGURE 7

Results further indicated that although the distance traveled may have increased to avoid contrails (Figure 6), the net radiative forcing output (sum of RF from CO2 and contrails) from ISSR avoidance caused lower RF as opposed to passing through ISSR. Figure 8 displays that for long duration flights, the RF (x-axis) was consistently lower for the more aggressive 1000 avoidance level (left) as opposed to the 100 level (right).

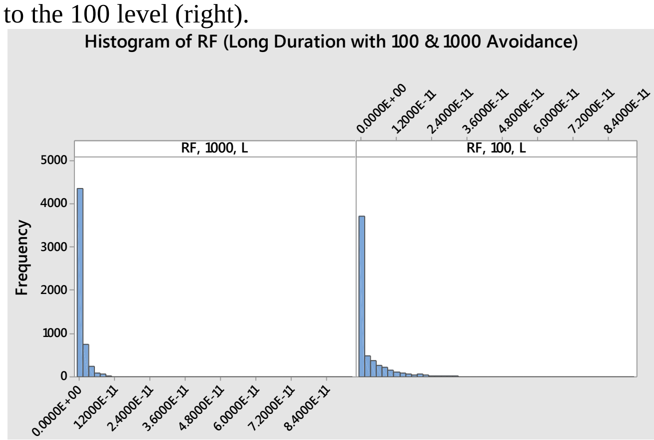

FIGURE 8

RECOMMENDATIONS AND CONCLUSIONS

Since radiative forcing due to contrails is always greater than the radiative forcing due to CO2 emisssions in the short time horizon (i.e. < 20 years), it is recommend a total contrail avoidance heuristic of 1,000 for all flights, (short, medium, and long-haul). This is further supported by the fact that aggressive ISSR avoidance as displayed in Figure 9 resulted in lower radiative forcing (RF).

There is a larger question that further research should address about who should pay for the extra fuel-burn and crew time required for the longer routes from contrail avoidance. Although society may benefit from reduced RF, airlines and their passengers will need to pay the extra costs for contrail avoidance. In some cases, such as the European Union, the societal benefit has been mandated in the form of user fees and a cap-and-trade scheme for CO2 emissions (reference). This is not the case in the U.S. and other parts of the world, where the impact of RF due to contrails and CO2 is not addressed.

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REFERENCES

[1] The New York Times, "U.N. Forecasts 10.1 Billion People by Century's End," 3 May 2011. Available: http://www.nytimes.com/2011/05/04/world/04population.html. Accessed 29 October 2013.

[2] U.S. Department of Transportation. "Form 41 and 298C- U.S. Regional Carrier Forecast Assumptions." http://www.transtats.bts.gov/databases.asp?mode_id=1&mode_desc=aviation&subject_id2=0. Accessed 20 September 2013.

[3] "Federal Aviation Administration," [Online]. Available: http://aspm.faa.gov/opsnet/sys/Airport.asp. Accessed September 2013.

[4] P. Minnis, "CONTRAILS AND CIRRUS CLOUDS," *NASA Langley Research Center,* 2005.

[5] "Market-Based Measures," International Civil Aviation Organization, [Online]. Available: http://www.icao.int/environmental-protection/Pages/market-based-measures.aspx.

[6] D. J. C. A. M. J. J. S. a. D. J. Q. Travis, "US jet contrail frequency changes: influences of jet aircraft flight activity and atmospheric conditions," *Int. J. Climatol,* p. 27: 621–632. doi: 10.1002/joc.1418, 2007.

[7] N. Y. C. H. K. N. Banavar Sridhar, "Fuel Effecient Strategies for Reducing Contrail Formations in United States Airspace," *29th Digital Avionics Systems Conference,* 2010.

[8] I. M. K. Geoffrey C. Bower, "MULTI-OBJECTIVE AIRCRAFT OPTIMIZATION FOR MINIMUM COST AND EMISSIONS OVER SPECIFIC ROUTE NETWORKS," *26th INTERNATIONAL CONGRESS OF THE AERONAUTICAL SCIENCES,* 2008.

[9] Lee, David. 2009. "Aviation and global climate change in the 21st century."