A CONTRAIL INVENTORY OF U.S. AIRSPACE (2015)

Denis Avila (Ph.D. Student), Lance Sherry (Ph.D.),
Center for Air Transportation Systems Research at George Mason University, Fairfax, VA.
Terrence Thompson (Ph.D.), The Climate Service, Asheville, N.C.

Abstract

High thin clouds are generated by aircraft when hot exhaust gases from the jet engines mix with cold, humid air. These anthropogenic (human made) clouds, known as condensation trails or "contrails," provide a net global warming effect. Although they block approximately 23% of the incoming shortwave radiation, they also reflect back to Earth approximately 33% of outgoing longwave radiation. Although the contrails generate only 2% of total anthropogenic radiative forcing they affect global warming immediately (unlike CO2 that affects global warning in 20-40 years). In this way contrails could be used to reduce global warming now to buy-time for CO2 mitigation initiatives to take effect. For this reason it is necessary to inventory contrails in the National Airspace System (NAS).

This paper provides an inventory of contrails for the U.S. NAS for 2015. The analysis is based on publicly available weather data, flight surveillance track data, models of contrail formation and persistence, and models of net radiative forcing. During this period an average flight schedule of 24,095 flights in 365 historic weather days generated a daily average of 83.7K nautical miles of contrails. The contrails resulted in an estimated daily net radiative forcing of +7.08 mW/m2. The diurnal effect was minimal, but the seasonal effect was significant: 63% of the total Contrail Along Track Distance was generated from June to September. Furthermore, less than 25% of the flights generated contrails on a given day and the most of the contrails are generated in the south-eastern United States. The implications of these results for contrail mitigation are discussed.

Introduction

Modern jet engine airliners cruising in the Troposphere, emit hot exhaust gases that mix with cold low pressure atmosphere resulting in the formation of condensation trails (i.e. contrails). The hot water vapor contained in the exhaust condenses and freezes on particles left by the engine creating an artificial cloud behind the aircraft. Under specific atmospheric conditions, known as Ice Super Saturation (ISS), these contrails can grow, spread and persist for up to 10 hours.

These anthropogenic (i.e. the result of human activity) high altitude thin contrail clouds have similar properties to high Cirrus clouds [1]. They are highly transparent to incoming shortwave radiation from the Sun and reflect outgoing longwave radiation back to Earth (Figure 1). Contrails exhibit a small albedo effect (i.e. cooling) by reflecting 23% of incoming radiation back out to space. The remaining incoming energy either reaches the Earth's surface (48%) or is absorbed by the atmosphere (23%). In addition to interacting with incoming radiation, these clouds, also absorb a portion of the outgoing longwave radiation, and reflect a fraction back to the surface (33%). As a consequence, the overall effect of contrails is to increase atmospheric greenhouse warming approximately 10% during the day and 33% at night [2].

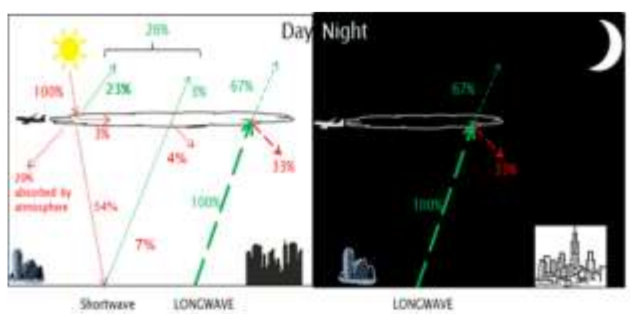

Figure 1: Effect of contrails on incoming shortwave radiation and outgoing longwave radiation.

The net contribution of contrails to global warming is almost negligible compared to other sources. The Intergovernmental Panel on Climate Change estimates total annual anthropogenic Net Radiative Forcing (NRF) at 2.38 W/m2 with aviation's total contribution 0.090 W/m^2 (3.7%) [3]. Contrails, estimated to cover 0.1% of the Earth's surface, have an estimated annual NRF of 0.05 W/m^2. This is equivalent to 55% of aviation's total anthropogenic NRF [1]. Contrail contribution to aviation NRF scales proportionally with the growth in aviation demand.

Unlike CO_2 emissions that impacts global warming on a 20-40 year time scale, the impact of contrails on global warming is immediate. In this way mitigating the global warming effects of contrails *today* could be a way to *buy time* to better manage CO_2 emissions and other sources of global warming in the future. In this way, a future scenario could see the need for "inventorying" contrails for Climate Change mitigation initiatives. This is analogous to the government requirement to inventory the quantity of pollutants (e.g. NOx, Sox, particulates, …) emitted in the vicinity of airports [4].

This paper describes the results of analysis of flight tracks for 365 days in the U.S. NAS. The analysis was conducted using a data analytic model based on the integration of models of net radiative forcing, and contrail formation. The model is described in detail in [5]. The main results are:

- On the average day, 7.4% of the volume of Contiguous United States (CONUS) between FL200 and FL400 exhibited Ice Super Saturated (ISS) conditions (sigma 2.63%)
- On the average day, only 25% of the flights traverse a CONUS Cell with ISS conditions.
- These 25% of the flights generate a daily average of 57.5K nautical miles of contrails (sigma 25K nm).
- The contrails result in an estimated average daily net radiative forcing of +7.8 mW/m^2.

During the day, the albedo cooling of incoming shortwave radiation of –1.84 mW/m^2 by the contrails is negated by the +5.85 mW/m^2 warming of trapped outgoing longwave radiation. At night the contrails trap outgoing longwave radiation +3.07 mW/m^2.

The largest magnitude contribution of contrails occurs in Summer months on flights on the U.S. eastern seaboard. Since of 25% of the flights generate contrails in a limited geographic area, the NRF effects of contrails may be mitigated by simple changes in Cruise Flight level in the Summer months for flights in south-eastern U.S.

This paper is organized as follows: Section 2 provides an overview of contrail formation and their effect on global warming. Section 3 describes the integrated method for estimating the surface area of contrails for a given day of atmospheric conditions and air traffic. Section 4 describes the results of analysis in the U.S. National Airspace System (NAS) in 2015. Section 5 describes the diurnal and season differences. The paper concludes with discussion of the implications of the method, limitations and future work.

Overview of Contrails and Global Warming

Aircraft impact the atmosphere in a visible way by forming contrails - artificially induced cirrus clouds. These clouds, predominantly composed of ice crystals with distinctive properties that are derived from the formation of the ice by hot exhaust gases, reflect certain wavelengths of radiation resulting in Radiative Forcing.

Contrails and Contrail Cirrus Clouds

Contrails are formed in a two a stage process: Formation, then Spreading. First, the Contrails are formed through “heterogeneous nucleation” when the hot water vapor, contained in the exhaust from jet engines, mixes with the cold low pressure atmosphere. The water condenses and freezes on particles left by the engine creating an artificial cloud behind the aircraft. The formation stage lasts for about 10 min.

Second, the Spreading phase can last up to 10 hours as atmospheric conditions allow. In the first hour, contrails grow rapidly horizontally to several kilometers in width and vertically to 200 to 400 meters. Over time, persistent contrails lose their initial linear shape and transition into contrail cirrus. They overlap and merge in traffic-congested areas, forming extended ice cloud layers that vary in shape, depth and lifetime. This freezing mechanism requires that the atmosphere be highly supersaturated with respect to the vapor pressure of ice before crystals can form.

Contrails often occur in clusters within regions that are cold and humid enough to allow persistent contrails to form, however, contrail coverage is determined by the number of aircraft flights in the necessary atmospheric conditions at cruise altitudes. In this way, contrails are not uniformly distributed; instead, they lie along air traffic corridors and accumulate near upper air route crossings. Aged contrails often cannot be distinguished from cirrus.

Global Warming and Radiative Forcing

Almost all of the energy that affects Earth's climate is received as radiant energy from the Sun. The planet, and its atmosphere, absorb and reflect some of the incoming energy, while long-wave energy is radiated back into space. The balance between absorbed and radiated energy determines the average global temperature. The radiation balance is by factors such as the intensity of solar energy, reflectivity of clouds or gases, absorption by various greenhouse gases or surfaces, and heat emission by various materials.

Radiative forcing is the difference between insolation (sunlight) absorbed by the Earth and energy radiated back out to space. Positive radiative forcing occurs when the Earth receives more incoming energy from sunlight than it radiates to space. This net gain of energy causes global warming. Negative radiative forcing occurs when the Earth loses more energy to space than it receives from the sun, which produces cooling.

Contrails and contrail cirrus clouds are thin and highly transparent to incoming shortwave radiation. They present a small albedo affect (i.e. reflecting incoming radiation back out to space), but allow most of the incoming energy to reach the Earth’s surface. These clouds also absorb a portion of the outgoing longwave radiation, and reflect a fraction back to the surface adding to the shortwave energy.

The overall effect of contrails is considered to increase atmospheric greenhouse warming [6][7]. A measure of the radiative imbalance of the atmosphere has been estimated from observed trends in cirrus cloudiness. Globally averaged, annual mean RF values for persistent contrails alone are 0.01 W/m^2 with an uncertainty range of (0.005–0.03 W/m^2) and together with contrail cirrus 0.05 W/m^2 with an uncertainty range (0.02–0.15) W/m^2

Method for Inventorying Contrails in a National Airspace System

A method to inventory contrails is described in [8]. The method processes publicly available archived track and weather data, and through contrail formation and net radiative forcing models.

The method for inventorying contrails in a National Airspace System (NAS) includes six processes (Figure 2). The first three processes identify the regions that meet the criteria for Ice Super Saturation (ISS). The fourth process generates the flight track data. The fifth process merges the weather and flight track data to estimate the contrails. The sixth process estimates the net radiative forcing.

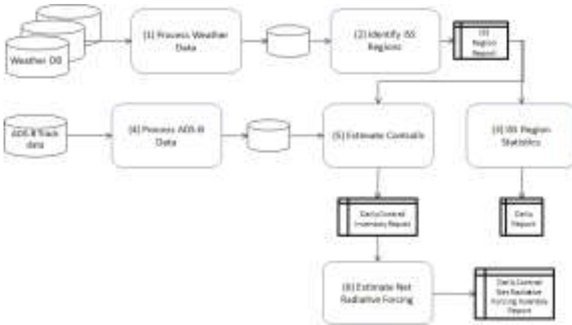

Figure 2 Six step processes to inventory contrails

Each of the six processes is summarized:

(1) Process Weather Data

Weather information is obtained from National Oceanic and Atmospheric Administration (NOAA) Rapid Refresh Products (RAP) weather files (http://www.nco.ncep.noaa.gov/pmb/products/rap/). These files provide information for a three-dimensional grid covering the CONUS (Figure 3). The grid cells are 13 km by 13 km by 1000 feet cells. The grid is formed starting at 16.28N/126.13W and extends to 55.48N/57.38W. The vertical dimension ranges from FL200 to FL400. There are 151,897 cells at each Flight Level, and a total of 2,431,792 three dimensional cells per hour.

Each hourly weather file is approximately 30MB of highly compressed data therefore each day entails over 58.3 million weather cells and 720 MB of compressed text, posing a challenge for both processing and storage. To mitigate this, as each file is decoded it is swept once, identifying ISS conditions as it is read. When identified the record is passed to a secondary procedure and immediately loaded to a database. The file is closed and no temporary space or files are required. Once loaded to the database the weather data is assigned to the latitude/longitude/altitude at the center of each cell.

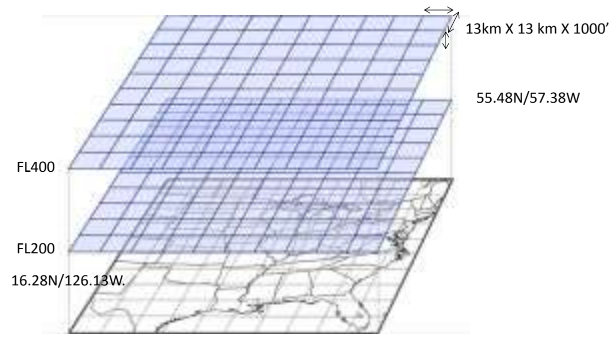

Figure 3: 13km X 13km X 1000' CONUS Cells of weather data.

(2) Identify Ice Super Saturated (ISS) Regions

The RAP data for each cell in the CONUS grid is evaluated. If the weather data for the cell meets the ISS criteria the CONUS cell is tagged as ISS conditions met. The ISS criteria are:

- Relative Humidity > 100%
- Temperature < -40 degrees Celsius

Specific Humidity data in the RAP file is translated into Relative Humidity. The Z pressure levels in the RAP data are translated into Flight levels.

(3) Ice Super Saturated (ISS) Region Statistics Report

Summary statistics for the ISS CONUS cells are generated. The report includes:

- Percentage of CONUS Cells presenting Ice Super Saturation (ISS) between FL200 to FL400
- Percentage of CONUS Cells presenting Ice Super Saturation (ISS) per Flight Level
- Ceiling and Floor of Ice Super Saturation (ISS) in CONUS Cells
- Geographic Coordinates of Ice Super Saturation (ISS) within the CONUS Cells
- Percentage of Rate of Change of Ice Super Saturation (ISS) within the CONUS Cells

The ISS regions can also be visualized in in 3-D image as shown in Figure 4 [5].

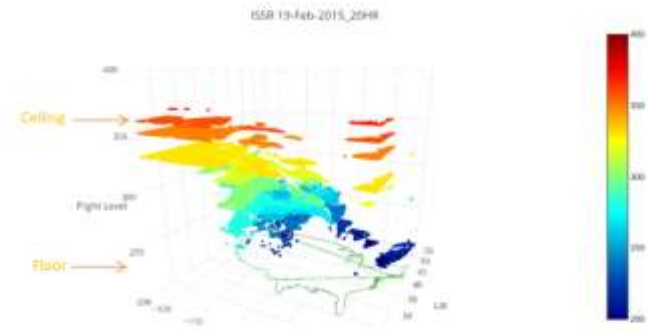

Figure 4: 3-D visualization of ISS Regions in the CONUS.

(4) Process ADS-B Data

The track data from the ADS-B files are processed. The data for each flight includes latitude, longitude, altitude, day and time. The update rate for records is variable from approximately 30 seconds to several minutes. Given the size of the CONUS cells, updates rates within one minute provide at least one record in each cell. Flights with gaps in track records > 5nm are eliminated, as are flights with along-track distance of less than 50nm, and flights with missing records.

The flights are categorized into Day and Night flights by taking the mid-point time between takeoff and landing. If the time at the halfway point of the flight falls between 6AM and 6PM the flight is considered a “Day” flight, otherwise it is considered as “Night” flight.

(5) Estimate Contrails

The contrail estimation is a two part process. First, each track for each flight is matched with the CONUS cells. When a track intersects with a CONUS Cells that meets the ISS criteria, a contrail “start time” is recorded.

In the second phase of this process is to calculate the persistence of the contrail by the evaluating the ISS conditions in that CONUS cell for every hour after the start time. Consistent with Jensen [9], the duration of the Contrail is extended for up to 5 hours or as long at the ISS conditions remain. Schumann [10] and Chen, Sridhar [11] estimate the size and duration of the contrail as 1000 m wide with a life of 10000 s (~2:45 hr) . Additionally Freudenthaler [12] estimated the lateral growth of contrails to range between 18 m / min and 140 m / min (between 1 and 8 km per hour).

Contrail assumptions: This analysis assigns a Contrail width of 500m for the first hour, 1000m, 2000m, 3000m, and 4000m for each subsequent hour that the ISS conditions exist. Crystal growth and optical depth parameters as set in section 6.

Contrail intersections points are aggregated by summarizing to every 10° both in latitude and longitude while retaining the actual flight level. To prevent duplication, such as cases where an aircraft was recorded in the same section multiple times, unique instances of weather grid locations are counted. Each identified Ice Super Saturated Region (ISSR) penetration is then multiplied by 7.02nm (I.e. 13 km) to estimate the along-track distance.

(6) Estimate Net Radiative Forcing

The effect of the radiative forcing (RF) at the top of atmosphere (TOA) produced by the contrails is calculated via the model developed by Schumann [10]. The model assumes a spherical ice crystal throughout the life of the contrail. The model estimates the radiative forcing as the sum of the longwave and shortwave effects as shown in the equation below. The net radiative forcing is the sum of the radiative forcing from longwave (RFLW) and from shortwave (RFSW).

$$RFNet = RFLW + RFSW$$

The details of the calculations are provided in Appendix A and Avila, Sherry [5]. The calculations take into account the size of the ice crystals and the solar zenith angle (SZA). The crystals are assumed to be spherical and their size is initiated at 10µm, increased to 20 µm at hour +1 and then held at 25 µm until hour +4 [13]. Optical depth is set to decrease hourly starting with 0.4, 0.2, 0.08, 0.02, 0.01 [10].

The models were verified by code inspection and test-case analysis. The contrail persistence and NRF model were validated by “order of magnitude” comparisons to satellite measurements and simulation models.

Inventory of Contrails in U.S. National Airspace System

The CONUS surveillance tracks from ADS-B transmissions of June 20th 2016, were matched against daily hourly weather data for 365 days from November 9 2014 to November 9 2015.

The results are organized as follows:

1. Flight Trajectory Statistics
2. Ice Super Saturated Region (ISSR) Statistics
3. Flight Trajectory Intersections with ISS CONUS Cells and Contrail Statistics
4. Net Radiative Forcing Statistics

Flight Trajectory Statistics

The sample day of flights, downloaded from the ADS-B Exchange (https://www.adsbexchange.com/), included 30,813 flights in the CONUS. Flight trajectories of less than 50 nm and flight trajectories with missing data were eliminated, leaving 24,095 flights (Table 1).

These flights generated 24.3M nautical miles along-track distance. Sixty nine percent (69%) of the along-track distance were generated during the day. The distribution of total along-track distance for each flight exhibits an exponential distribution with a mean of 952 nautical miles and a median of 531 nautical miles.

The flight trajectories traversed 316,495 CONUS cells. Sixty three percent (63%) of the CONUS cells were traversed during daylight hours. The distribution of CONUS cells traversed is Exponential with median of 10 and mean of 13.3 CONUS cells.

The flights operated with Cruise Flight levels ranging from FL200 to FL 400. The Mean and median Cruise Flight Level was FL 350. Fifty-five percent (55%) of the flights had Cruise Flight Levels between FL340 and FL360

Table 1: Summary Flight Trajectory Statistics for June 20th 2016.

Statistic	Daily Total
Flight Count	24,095 flights
Flight Trajectory Along-track Distance (ATD)	24,363,179 nm
Flight Trajectory Count CONUS Cells	316,495 CONUS cells

Ice Super Saturated Region (ISSR) Statistics

Weather data from November 9 2014 to November 9 2015, was analyzed. The weather data was downloaded from the National Oceanic and Atmospheric Administration (NOAA) Rapid Refresh Products (RAP) weather files (http://www.nco.ncep.noaa.gov/pmb/products/rap/). Relative Humidity and Temperature were established for the 151,987 CONUS cells for each Flight Level, from FL200 to FL400.

On the average day, Ice Super Saturated (ISS) conditions were present in 7.4% of the CONUS cells with standard deviation 1.5 % of the cells (Table 2).

Due to diurnal effects, the nighttime exhibits an average of 2.5% more CONUS Cells with ISS conditions. During the daytime, the CONUS cells with ISS conditions were normally distributed with an average and median of 6.2% of the CONUS with a standard deviation of 1.2%. During nighttime, the CONUS cells with ISS conditions were also normally distributed with an average and median of 8.7% with standard deviation of 1.6%.

Table 2: ISSR Statistics for 365 days of weather

Statistic	Daily Total	
	µ	Std Dev
Daily Average ISS CONUS Cell Count	178,516 (7.4%)	33,796 (1.5%)

Flight Trajectory Intersections with ISS CONUS Cells

The sample day of 24,095 flights in the CONUS traversed a total of 242,704 CONUS cells. The average percentage of flights that traversed ISS CONUS Cells each day was 22.3% with standard deviation of 6.9% (Table 3). Fifty eight percent of flights that traversed ISS CONUS cells were daytime flights.

On the average day, the flights in the CONUS ISS cells generated 57,472 along-track nautical miles of contrails (Figure 5).

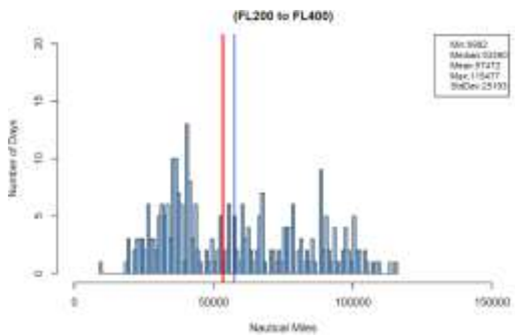

Figure 5 Contrails generated in the US Airspace

The contrail along-track distance is above the annual average in the Summer months. The daytime contrail along-track distance is on average 21% greater than the nighttime contrail along-track distance.

The average contrail along-track distance (ATD) for flights that traverse a CONUS cell with ISS conditions is 9.3 nautical miles.

Table 3: Flight Trajectory Intersections with ISS CONUS Cells

Statistic	Daily Total	
	μ	**Std Dev**
Flights that traversed ISS CONUS Cells	6,160 (22.3%)	1,931 (6.9%)
Along-track Distance of Contrails Generated (nm) per day	57,472 (0.3%)	25,186 (0.15%)

Net Radiative Forcing Statistics

The Net Radiative Forcing (NRF) is: the sum of

- the outgoing longwave radiation reflected back to the Earth during the day (i.e. warming)
- the outgoing longwave radiation reflected back to the Earth during the night (i.e. warming)
- the incoming shortwave radiation reflected back out to space (i.e. cooling).

For the year, the estimated total NRF generated by the contrails had a net warming effect of magnitude 206 W/m^2. This includes an annual albedo cooling during the day of 0.670 W/m2, warming of 2.1 W/m2 and 1.4 W/m2.

The estimated daily average was 7.08 mW/m^2 with a median 6.44 mW/m^2 (Figure 6). The NRF exhibits a high degree of variance with a standard deviation of 3.59 mW/m^2 which is roughly half of the mean (i.e. coefficient of variation is 0.5). Since the analysis was conducted with the same daily flight schedule, the variance is derived from volume, altitude, and geographic location of the ISS regions.

Table 4: Daily Estimated Net Radiative Forcing

Statistic	Daily Total	
	μ	Std Dev
Daily Estimated Net Radiative Forcing (mW/m^2)	7.08	3.59

The NRF in the U.S. is above average in the Summer months and below average in the Winter, Spring and Fall. There are 9 days in this period in which NRF exceeds 2 sigma.

The average NRF per flight is 0.0003 mW/m^2. The average NRF per contrail flights is 0.00115 mW/m^2.

The average NRF per along-track distance nautical mile is 2.9 x 10-7 mW/m^2. The average NRF per contrail along track distance nautical mile is 0.00012 mW/m^2.

5 DIURNAL AND SEASONAL IMPACTS

The CONIS ISS cells, the number and routing of flights, and the sources of radiation (i.e. shortwave from the Sun and longwave from the Earth) combine to exhibit diurnal and seasonal effects.

Diurnal Effects

The complex relationship between flight routes and cruise flight level, CONUS ISS, and NRF for day and night flights is summarized in Table 5. Although there are only 30% more flights in the day than the night, the day time Along Track Distance is twice that of the night. This is a consequence of the routes flown, the cruise flight levels selected, and the location of the CONUS ISS cells. This day time advantage is mitigated by the lower count of CONUS ISS cells during the day.

Although here are 47% more day time flights that generate Contrails than flights that generate contrails in the night, the day time flights generate

58% more Contrail Along Track Distance. This results in a 31% higher NRF in the day than in the night. The (cooling) albedo effect during the day is out weighted by the higher number of flights. During the day, the albedo cooling of incoming shortwave radiation of –1.84 mW/m^2 by the contrails is negated by the +5.85 mW/m^2 warming of trapped outgoing longwave radiation. At night the contrails trap outgoing longwave radiation +3.07 mW/m^2.

- Night time flights 0.00029330276 mW NRF per flight
- Day time flights 0.00029424713 mW NRF flight

Table 5: Comparison between Day and Night.

Statistic	Day	Night	Day/Night Ratio
Daily Flights	13,628	10,467	1.3 56.56% Day
Total Along Track Distance	16,553,906 nm	7,809,273nm	2.12 68.9 % Day
Daily Average CONUS ISS Cell Count	151,442 (6.2% of Total CONUS Cells)	211,167 (8.7% of Total CONUS Cells)	0.72 (42% Day)
Daily Average Count of Flights that Generate Contrails	3,593 (15% of Total Daily Flight)	2,567 (11% of Total Daily Flights)	1.47 58.32% Day
Daily Average Contrail Along Track Distance	34,785 nm	22,879 nm	1.58
NRF	4.01 mW/m^2 (–1.84 mW/m^2 + 5.85 mW/m^2)	+3.07 mW/m^2	1.31 56.67% Day

Seasonal Effects

The complex relationship between flight routes and cruise flight level, CONUS ISS, and NRF for the four "summer" months of June, July, August and September versus the remaining eight months of the year is summarized in Table 6. Although the number of flights in the 4 summer months is half the number of flights in the non-summer months, these flights generate 25% more Contrail ATD and 30% more NRF.

Table 6: Comparison of Summer months with Non-summer months

Statistic	Summer Months (June, July, Aug, Sept)	Not Summer Months	Summer/Not Summer Ratio
Total Flights	96,380.00	192,760	0.5
Total Contrail Along Track Distance (nm)	9,900,233	5,962,039	1.66
Total NRF	1,269	685	1.85

During the Summer months, the volume of ISS CONUS cells are greater than the volume of ISS CONUS Cells in the non-summer months. The average percent of the CONUS with ISS Cells in the "summer" was 8.4% with an average in the "winter" of 6.3% (significant at $p < 0.05$).

In addition to the less humid conditions in the non-summer months, the ISS CONUS ceiling is lower in the winter months than the summer months allowing more aircraft to cruise above the ISS CONUS cells.

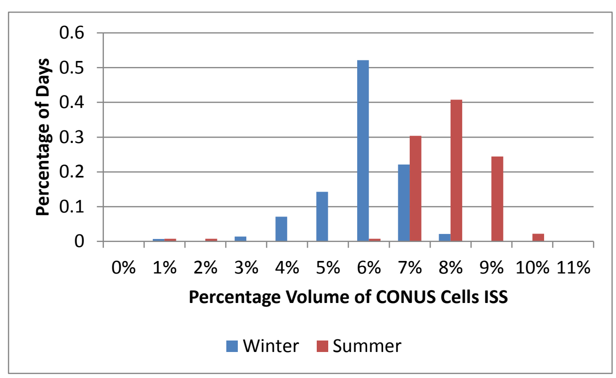

Figure 6: Percent of CONUS Cells between FL200 and FL400 that exhibit Ice Super Saturated Conditions in "summer" and "winter" months.

Geographic Location

Twenty percent of the vertical CONUS volumes (i.e. from FL 200 to FL400) generate 50% of the Contrail flights (Figure 7). These vertical CONUS volumes are east of the Mississippi and south of New York state.

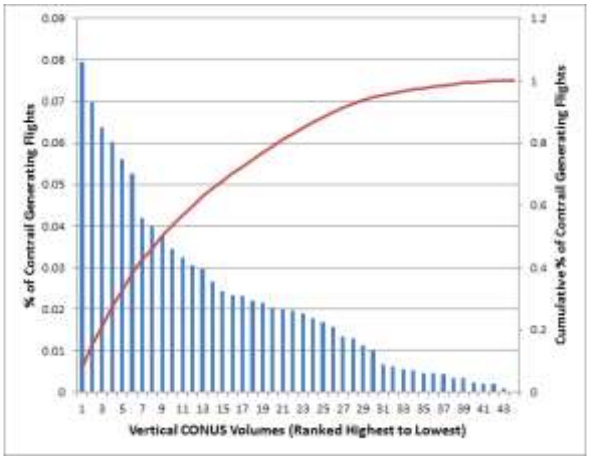

Figure 7: Twenty percent of the vertical CONUS volumes (i.e. from FL 200 to FL400) generate 50% of the Contrail flights

Conclusions

Contrails provide an important component of a global warming mitigation portfolio. Although the impact of contrails on global warming is relatively low (2% of total anthropogenic radiative forcing), contrails have the characteristic that their radiative forcing has *immediate impact* on the planets temperature. In contrast CO_2 emissions today have an impact on global warming on a 20 – 40 year time scale. In this way managing contrails could be a way to lower temperatures now to buy time to mitigation strategies for CO_2 emissions and other sources of global warming to take effect.

This paper estimated the annual contrail inventory for a full year (2015) for the contiguous U.S. national airspace for 365 weather days. On the average day, 7.4% of the volume of Contiguous United States (CONUS) between FL200 and FL400 exhibited Ice Super Saturated (ISS) conditions (sigma 2.39%). These ISS regions were traversed on the average day by 6,160 flights (25%) and generated a daily average of 57.5K nautical miles of contrails (sigma 25K nm).

Key Findings for Global Warming Mitigation

The analysis described in this paper identified that 50% of the contrail generation occurs in the south-eastern United States. The contrails are generated predominantly in the Summer months (June – September). There is no diurnal advantage. When the frequency of flights is taken into account, mitigating contrails at night is not much better than mitigating contrails during the day.

These results indicate an opportunity to perform contrail mitigation on a small, limited set of flights. Benefits of Contrail mitigation using Cruise Flight Level changes has been demonstrated by Evans et. al. [11], Sridhar [14] and Gao & Hansman [15].

Limitations and Future Work

This study was conducted using 365 weather days from the NOAA data-base. The flight routes and Cruise Flight Levels were constant representing one "summer" week day. This approach was used to avoid the complexity in interpreting the results by confounding flight routes and cruise flight level changes. In this way the flight routes and cruise flight levels used do not reflect seasonal route adjustments that may occur such as jet stream changes and seasonal Cruise Flight Level changes due to outside air temperature (OAT) differences. It would be a natural follow-on to conduct the same study with flight tracks from each day, or one day of flight tracks from each month.

References

[1] Kärcher, B. Formation and radiative forcing of contrail cirrus. Nature Communications. 10.1038/s41467-018-04068-0 2018

[2] Trenberth, K., J. Fasullo, J. Kiehl (2009). Earth's global energy budget. Bulletin of the American Meteorological Society.

[3] Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang, 2013: Clouds and Aerosols. Supplementary Material. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group. I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

[Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Available from www. climatechange2013.org and www.ipcc.ch.

[4] National Academies of Sciences, Engineering, and Medicine. 2013. Guidebook for Preparing Airport Emissions Inventories for State Implementation Plans. Washington, DC: The National Academies Press. https://doi.org/10.17226/22590.

[5] Avila D, Sherry L. Method for Calculating Net Radiative Forcing from Contrails from Airline Operations. 2017 Integrated Communications, Navigation, Surveillance (ICNS) Conference.

[6] Working Group I, (2013) IPCC. Summary for policymakers. In Climate Change 2013: The Physical Science Basis. Contribution of WG I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (eds. Stocker, T. F. et al.) (Cambridge UniversityPress,Cambridge,UK,andNewYork,NY,USA,2013).

[7] Brasseur, G. P. (2016) Impact of Aviation on Climate — FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II. Bull. Am. Meteor. Soc. 97, 561–583 (2016).

[8] Avila D, Sherry L, Thompson T. Design of Ice Super Saturated Region (ISSR) Visualization Tool for Contrail Planning. IEEE ICNS Conference 2018

[9] Jensen E, Environmental conditions required for contrail formation and persistence. Journal Of Geophysical Research, Vol. 103, No. D4, Pages 3929-3936, February 27, 1998

[10] Schumann U., B; K. Graf, H. Mannstein. A Parametric Radiative Forcing Model for Contrail Cirrus. Institute for Atmospheric Physics - Ulrich Schumann, Germany . 2012

[11] Evans, A. Chen N, Sridhar, B., H.K. Ng. (2012) Tradeoff between Contrail Reduction and Emissions under Future US Air Traffic Scenarios. 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM 17 - 19 September 2012, Indianapolis, Indiana

[12] Freudenthaler Homburg F, Jäger H., Contrail observations by ground- based scanning lidar: Cross- sectional growth. Geophysical Research Letters Fraunhofer Institute for Atmospheric Environmental Research (IFU). Kreuzeckbahnstr. 1995

[13] Schröder F, Kärcher B, On The Transition Of Contrails Into Cirrus Clouds, Journal Of The Atmospheric Science, 1999

[14] Sridhar, B., H. K.Ng, , F. Linke, N.Y. Chen(2014) Benefits analysis of wind-optimal operations for trans-Atlantic flights. In 14 th AIAA Aviation Technology, Integration, and Operations Conference (American Institute of Aeronautics and Astronautics, Atlanta, GA, 2014).

[15] Gao, H., and R. J. Hansman (2013). Aircraft Cruise Phase Altitude Optimization Considering Contrail Avoidance. Master's Thesis, Department of Aeronautics, Massachusetts Institute of Technology. Report No. ICAT-2013-10. Sept. 2013. MIT International Center for Air Transportation (ICAT). Department of Aeronautics & Astronautics. Massachusetts Institute of Technology. Cambridge, MA 02139 USA

Acknowledgements

The authors acknowledge the technical contribution and comments from Elise Miller-Hookes (George Mason University), George Donohue, John Shortle, Tom Clemmons, Paulo Costa, Seungwon Noh, Sasha Donnelly (Center for Air Transportation Systems Research at George Mason University), Mark Klopfenstein (AVMet), Akshay Belle (Booz Allen Hamilton).

Email Addresses

lsherry@gmu.edu.

davila@masonlive.gmu.edu