REDUCING GLOBAL WARMING BY AIRLINE CONTRAIL AVOIDANCE:

A CASE STUDY OF ANNUAL BENEFITS FOR THE CONTIGUOUS UNITED STATES

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Abstract:

High thin clouds are generated by airliners when hot exhaust gases and water vapor from the jet engines mix with cold, humid air to form high thin clouds. These anthropogenic (human made) condensation trails, or "contrails," create a green-house effect by absorbing or directing back to Earth approximately 33% of emitted outgoing longwave radiation. Although this effect is estimated to be less than 2% of the Earth's total anthropogenic radiative forcing, the effect on global warming is immediate, unlike CO_2 emissions which have a two decade delay in affecting global warming. Policy makers and industry have asked what is the potential for mitigating contrails through operational changes in air traffic control and flight planning.

Previous research calculated contrail inventories for the whole U.S. National Airspace System (NAS) over one year: on an average day only 15% of the flights (34% maximum) generated contrails, most of the contrails were generated in the south-eastern United States and the Pacific coast, and 63% of the total Contrail Along Track Distance was generated from June to September. This information suggests a possibility of mitigating the green-house effect of contrails by seasonally targeting a small set of flights.

This paper describes the benefits of adjusting the Cruise Flight Level of a limited number of flights in the U.S. NAS that are flight planned to fly through Ice Super Saturated (ISS) regions that are conducive to the formation of persistent contrails. The analysis found that elevating the Cruise Flight Level of contrail generating flights by 2000' or 4000', reduced the number of average daily flights with contrails by an average of -14.8%, the Net Radiative Forcing by an average of -92%, with an average net small decrease in fuel-burn of less than one percent (due to lower Drag at higher altitudes). The implications of these results and the limitations of the method are discussed.

INTRODUCTION

Modern jet engine airliners emit hot exhaust gases and water vapor at high altitudes that mix with cold, low pressure atmosphere resulting in the formation of visible condensation trails (also known as contrails). The hot water vapor exhausted by the jet engines, 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 redirect back to Earth the emitted outgoing longwave radiation. This increases atmospheric greenhouse warming approximately a net of 10% during the day and 33% at night [2]. See Figure 1.

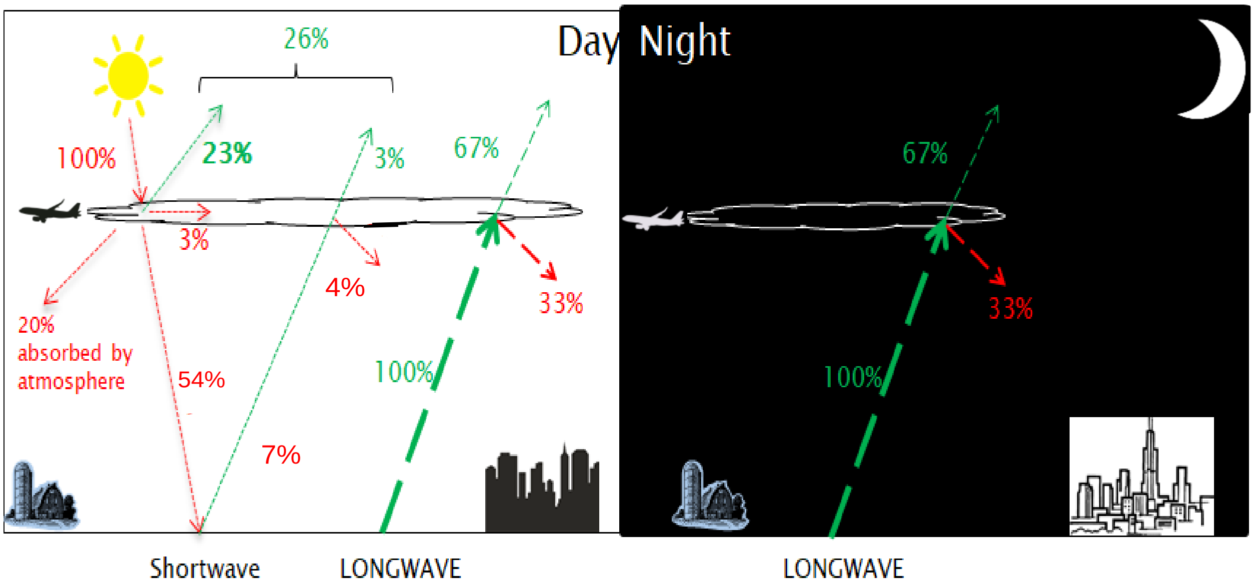

FIGURE 1: Effect of contrails on incoming shortwave radiation and outgoing longwave radiation.

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], [4]. Contrails, which are estimated to cover 0.1% of the Earth's surface, have an estimated annual NRF of 0.05 W/m^2. In this way, although contrails contribution to global warming is on the order of approximately 2%, it is 55% of aviation's total anthropogenic NRF [1]. The percent contribution of contrails is expected to grow proportional to the growth in aviation. Unlike CO_2 emissions today that impact global warming in 20-40 years, the impact of contrails on global warming is *immediate*. In this way, if the aviation community could reduce the number of contrails, it could *buy time* to better manage CO_2 emissions and other sources of global warming in the future.

Policy makers and industry have asked what is the potential for mitigating contrails through operational changes in air traffic control and flight planning for the U.S.

Previous research [5], [15] inventoried contrails in the contiguous United States (CONUS) for one year (2015). The analysis identified that: (i) two-thirds of the contrails are generated in the Summer months, (ii) only on average 15% of the flights each day (maximum 34%) generate contrails, and (ii) the contrail generation is mostly limited to geographic regions of the in south-east/mid-west and on the Pacific coast.

Others research on the impact of contrail avoidance on a flight-by-flight basis demonstrated that flying around contrails (i.e. lateral path offset) at the same Cruise Flight Level is not cost effective due to the significant width of the Ice Super Saturated regions, but that flying over contrails in certain circumstances can have net benefits [6], [7], [8], [9]. This previous research focused on the cost and benefits on a flight-by-flight basis (not on the aggregate benefits to a national airspace system).

This paper describes the results of analysis of a concept-of-operations for the National Airspace System (NAS) for the contiguous U.S. (CONUS) whereby flights planned with routes that are forecast to traverse ISS regions of the airspace, modify their flight plans to fly over the ISS regions on the same lateral path. The Cruise Flight Level would be increased by either 2000' or 4000' not to exceed FL400. The analysis is conducted for a representative daily schedule of scheduled airline flights with their actual flight plans (i.e. Cruise Flight Levels, and lateral flight plans) for a full year of hourly atmospheric conditions. The concept-of-operations was to increase the Cruise Flight Level by 2000' (or 4000' if needed) for flights with routes planned to traverse regions conducive to generating contrails.

The results of this analysis described in this paper indicated an estimated average daily decrease of -63% in NRF with a 2000' increment in Cruise Flight Level, and an average daily decrease of -92% in NRF with up to a 4000' increment in Cruise Flight Level. These changes were considered statistically significant when compared to the original Cruise Flight Level at the 99% confidence interval. The difference in Fuel Burn between trajectories with the Original Cruise Flight Level and Fuel Burn with the incremental Cruise Flight Levels were *not* statistically significant. Additional Fuel Burn for climb and descent was counter-balanced by the lower Drag at higher altitudes for long duration cruise segments.

It should be noted that the formation of contrails and their impact on climate change is a complex, evolving science. For example, RF cannot be observed directly and is therefore obtained with the help of models or by extrapolation of regional values inferred from satellite observations. In this way all estimates of NRF are subject to uncertainty bounds estimated at 90% [3]. For a retrospective of confidence intervals of RF estimates of contrails see [1, Figure 7]. The models used in this paper are derived from the latest peer-reviewed scientific publications.

This paper is organized as follows: Section 2 provides a description of the proposed concept-of-operations. Section 3 describes the method of analysis. Section 4 describes the results of analysis in the U.S. National Airspace System (NAS) for 365 ISS days in 2015. Section 5 concludes with a discussion of the implications of the method, limitations and future work.

CONTRAIL MITIGATION CONCEPT-OF-OPERATIONS

The aviation community can contribute to climate change efforts by reducing anthropogenic global warming by a reduction in the contrails generated. The concept is to exploit the facts that only a limited number of flights generate contrails in finite geographic area. It also might be beneficial to exploit the seasonal effects (i.e. Summer months).

Flight Planning

Contrail avoidance would be conducted as part of the standard flight planning process conducted for all flights including Part 121 scheduled operations (i.e. airlines). In addition to wind optimum routing, the flight plan could also be checked and optimized for contrail avoidance [8], [9]. The flight plan would be modified by increasing the Cruise Flight Level by 2000’ or 4000’ (if needed) in accordance with Domestic Reduced Vertical Separation Minimum (DRVSM) rules. To incentivize participation, airlines could be given credits for priority in Traffic Flow Management initiatives such as the Ground Delay program (GDP) or Air Flow Program (AFP).

Avoiding Ice Super Saturated Regions

There are two ways to avoid the ISS regions: (1) fly around the perimeter, or (2) fly over/under.

The horizontal width of ISS regions makes routing around the ISS region prohibitive. For example, for the CONUS ISS regions on November 15, 2014, north-south flights from southern Florida would have to skirt a wide berth as far away as Texas to avoid the ISS region (Figure 2). The same is true for north-south flights from southern California. Other studies found that lateral re-routing generated additional fuel burn costs that exceeded the environmental benefit [6], [8], [9].

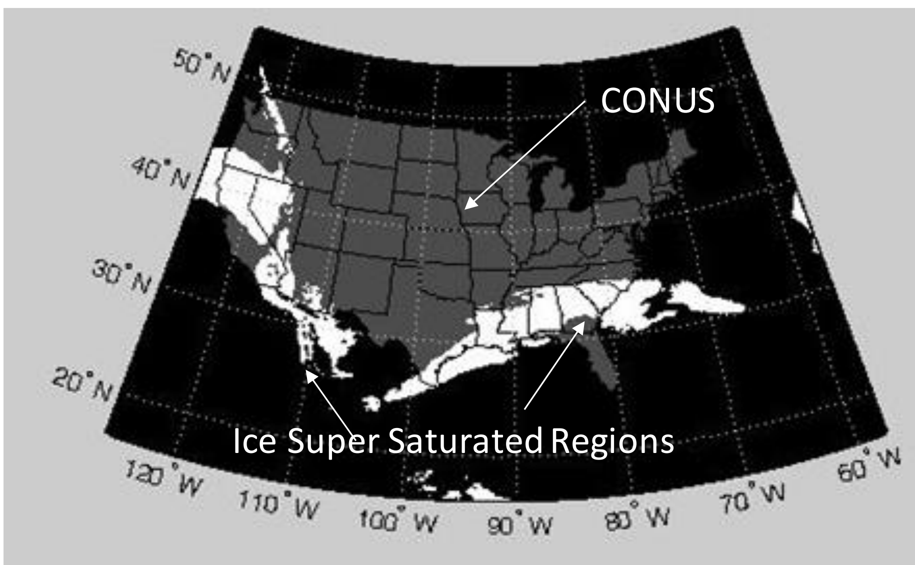

FIGURE 2: Size of ISS region adds significant distance to lateral re-route for north-south flights from southern Florida on the east coast and from southern California on the West coast. ISSR at Flight Level 360 at 9:00 AM on November 15th 2014.

Matching Ice Super Saturated Regions and Cruise Flight Levels

Ice Super Saturated (ISS) Regions and preferred Cruise Flight Levels overlap. Analysis of National Oceanic and Atmospheric Administration (NOAA) Rapid Refresh Products (RAP) atmospheric data for the CONUS in the year 2015, shows the percentage of ISS coverage at each Flight Level by an

ISS region is 76% cumulative between FL320 and FL350 [5]. Note the significant drop-off to only 7% at FL 370 (Figure 3).

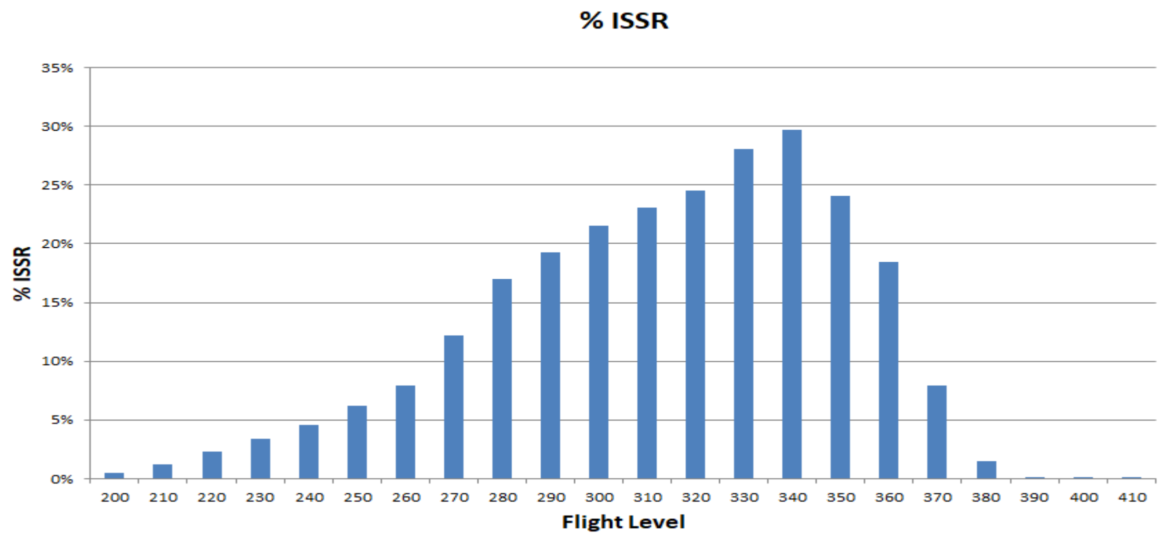

Figure 3: Percent ISSR coverage by Flight Level peaks at FL 350 and drops radically at FL 360 and above. ISS data for CONUS 2015.

In contrast, an analysis of flight trajectories in the CONUS for June 20, 2016, showed that 71% of the flights in the U.S. NAS cruise between FL320 and FL350 [15]. The preferred Cruise Flight Levels has a mode at FL340 (Figure 4). By comparing the two charts, on aggregate, there is overlap between the preferred Cruise Flight Levels and the predominant location of ISS regions. However a small increase in Cruise Flight Levels, in accordance with Domestic Reduced Vertical Separation Minimum (DRVSM) rules, could move flights out of the ISS regions.

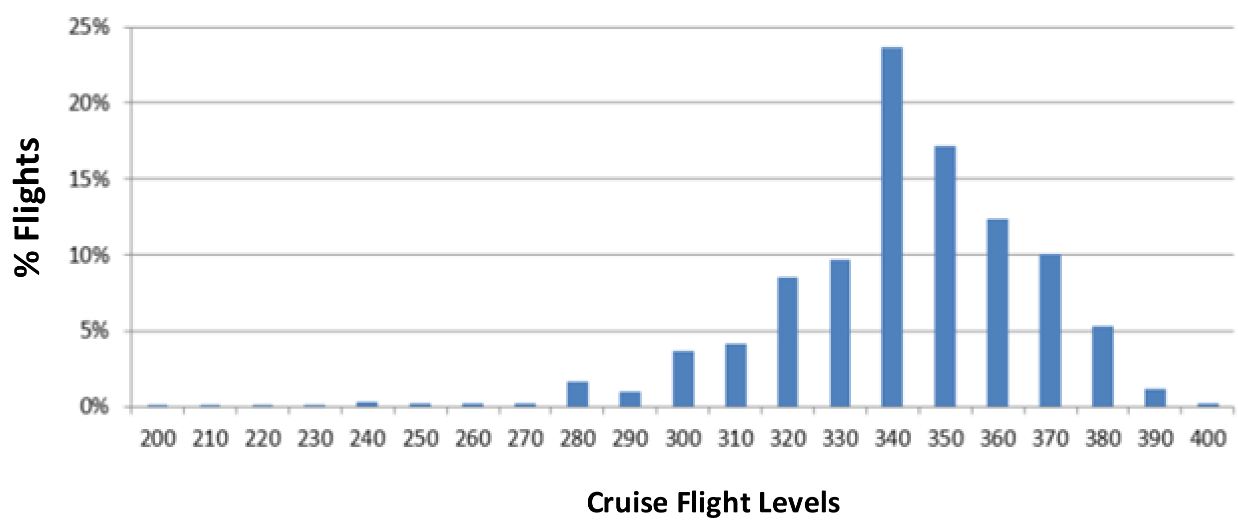

Figure 4: Distribution of contrail generating flights by Cruise Flight Level has 30% of the flights already operating in ISS-free airspace above FL350.

The next section describes a big-data analytic method for evaluating the global warming benefits of contrail avoidance with additional costs in Fuel Burn. The section after that describes a case study for one year of flights in the U.S. NAS.

METHOD FOR REAL-TIME ANALYSIS OF ALTERNATE CRUSE FLIGHT LEVESL FOR CONTRAIL AVOIDANCE

This section describes a big-data analytical method to rapidly evaluate the effect on NRF and Fuel-burn for the same lateral flight plan but with alternate Cruise Flight Levels (Avila, 2019). The process calculates the benefits in NRF and the costs in Fuel-burn for increasing a flights Cruise Flight level by 2000’ and (4000’ if needed).

The method includes a seven step process summarized in Figure 5.

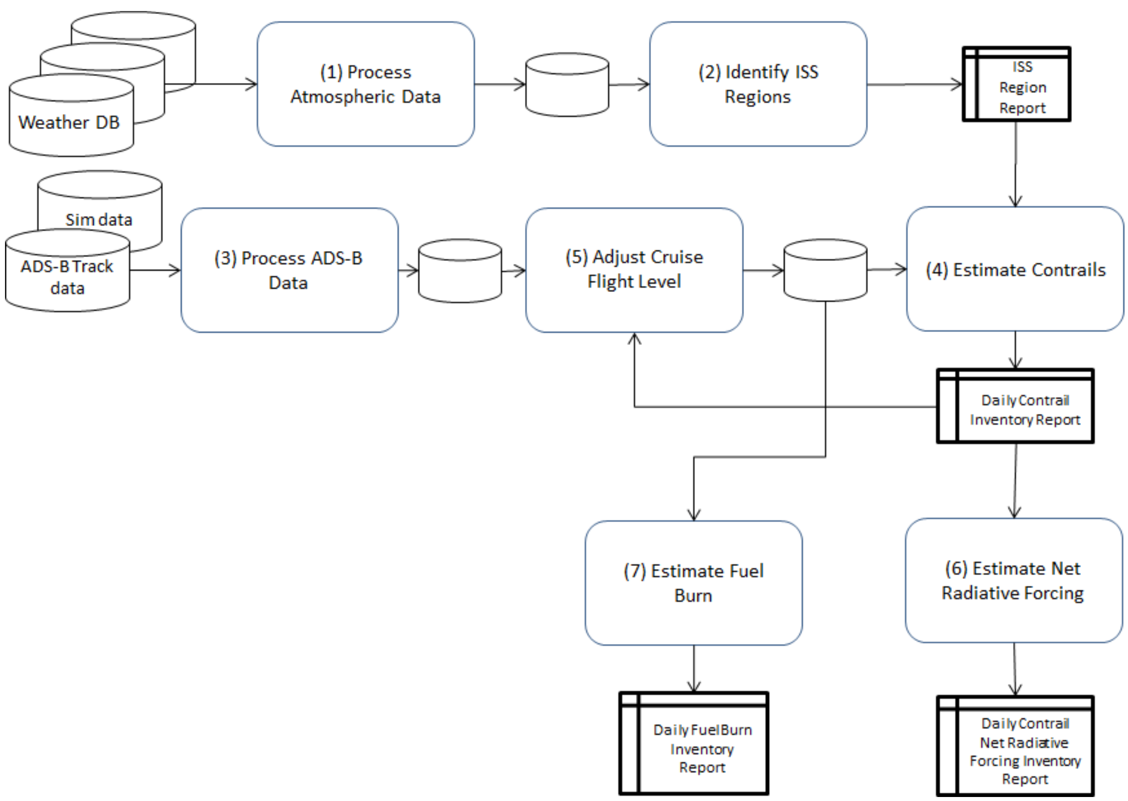

FIGURE 5: Seven step process for estimating the effect of alternate cruise flight levels for contrail generation, fuel burn and RF.

Step 1: Process Atmospheric 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 6). 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.

The weather information is processed and stored as N_x, N_y, Z coordinates located in the grid over the CONUS There are 151,897 cells at each Flight Level, and a total of 2,431,792 three dimensional cells per hour.

Hourly weather data determines the change of ice-super saturated regions in size and location over time. Each weather cell is uniquely identified within the grid based on its latitude and longitude and assigned a location Identifier (LocID) and can be identified by its LocID (1 to 151,897) and a Flight Level.

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 an ISS is identified, the record is passed to a secondary procedure and immediately loaded to a database. The file is closed and no temporary storage 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.

Using the potential weather cells, the process creates a subset of the atmospheric data. The subset will be limited to the latitude and longitude combinations found for flight trajectories while including all possible altitudes. This step proved critical at a later stage as it reduced the universe of the ISSR cells from 1.1 billion to 189 million.

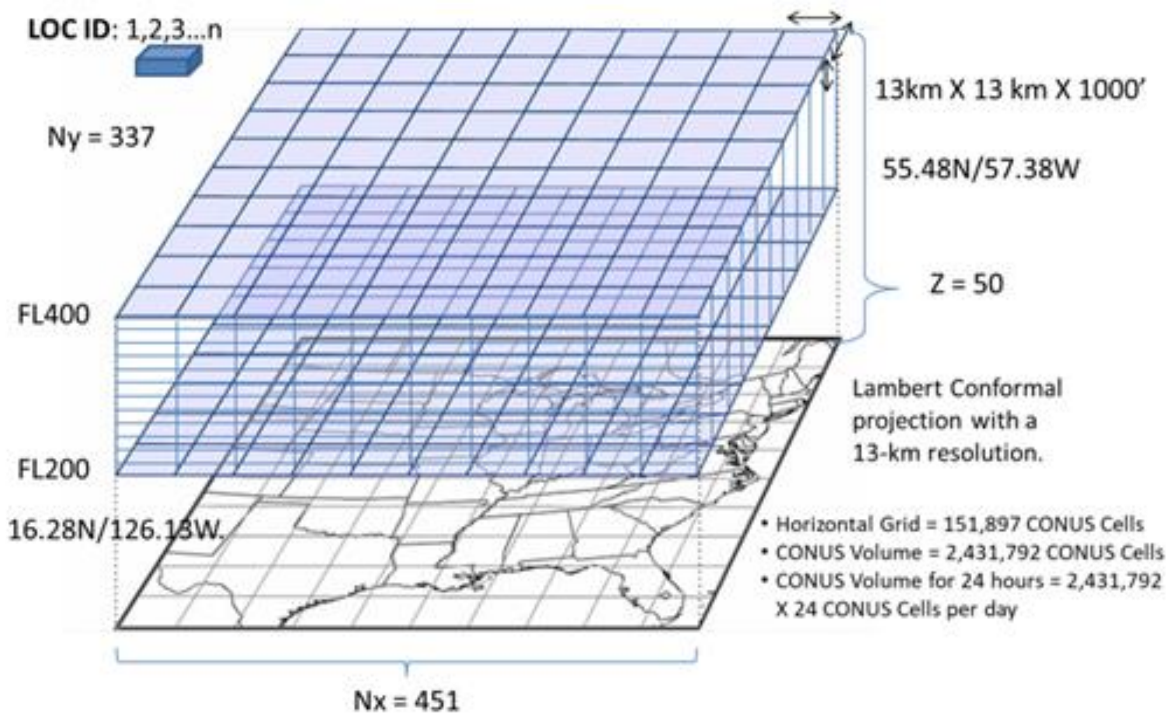

Figure 6: CONUS Weather grid. Cells are 13km X 13km X 1000'

Step 2: Identify ISS Regions

If the atmospheric data for the cell meets the ISS criteria, the CONUS cell is tagged. The Schmidt-Appleman criteria [10] for ISS are:

- Relative Humidity > 100%
- Temperature < -40 degrees Celsius at Standard Pressure

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. The temperature threshold of –40 degrees Celsius is adjusted for ambient pressure.

Step 3: Process Flight Data

Flight track data can be generated from a flight plan with waypoints, cruise flight levels and velocities for each waypoint. Alternatively, track data from the ADS-B files can be processed. The flight track data for each flight includes latitude, longitude, altitude, day and time. The update rate for ADS-B track data 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. ADS-B 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.

Flight paths are assembled taking the points along the path for each flight and mapping the position to a weather location. This process takes the latitude and longitude of each point and locates the position within a specific weather cell to assign a unique Weather location ID. In a similar way the altitude is mapped to a weather pressure level (Z level)

Step 4: Estimate Contrails

The flight trajectories are matched to atmospheric ISS locations independent of aircraft altitude to create a subset of the weather data that identifies all potential locations for contrail formation for that set of trajectories. The contrail space is generated matching location, date and time for the original Cruise Flight Level. If the conditions for a contrail to form and persist are met (i.e. the Schmidt-Appelman Criteria: Relative Humidity > 100% and Temperature < -40 degrees Celsius), a contrail is generated. The contrail will persist for an additional 4 hours (i.e. maximum 5 hours) if the Relative Humidity and Temperature conditions remain present. The Contrail Along-track Distance is calculated by the distance between the first CONUS cell with a contrail and the last CONUS cell with a contrail for each trajectory. The width of the contrail is a function of the duration as shown in Table 1.

TABLE 1: Width of Contrail based on Contrail Duration

Hour of Contrail Duration	Width (m)
1	500
2	1000
3	2000
4	3000
5	4000

Step 5: Adjust Cruise Flight Levels

The Cruise Flight Level is adjusted up by 2000' if the original Cruise Flight Level generates a contrail. If the Cruise Flight Level + 2000' generates a contrail, the original Cruise Flight Level is increased by 4000'.

Step 6: Net Radiative Forcing Model

The effect of the Radiative Forcing (RF) at the top of atmosphere (TOA) produced by the contrails is calculated based on the model developed by Schumann [12]. A spherical ice crystal is used throughout the life of the contrail. The contrail width is set to 500m for the first hour, 1000m, 2000m, 3000m, and 4000m for each subsequent hour that the ISS conditions exist (i.e. Relative Humidity > 100% and Temperature < -40 degrees F). Optical depth parameters are set based on [11] & [1]: the diameter of the crystals grow from approximately 1 to 10 micro-meters over the first 30 minutes, then stabilizes between 20 and 30 micro-meters.

The model [12] estimates the Net Radiative Forcing (NRF) as the sum of the incoming solar shortwave radiation (RF_{SW}) and outgoing longwave radiation (RF_{LW}):

$RF_{Net} = RF_{LW} + RF_{SW}$

Longwave Radiation Calculation:

RF_{LW} = [OLR –k_T(T-T_0) {1-exp[δ_τ $F_{LW}(r_{eff})\tau$]} $E_{LW}(\tau_c) \geq 0$

The outgoing longwave radiation, OLR, is set to 275 W/m^2 OLR value is based on the OLR recorded by NOAA during June 2016. Three sample were extracted to show high and low values. The OLRs sampled corresponded to 329, 194 and 274 W/m^2. The optical depth τ is estimated based on findings from [14]. T is temperature in Kelvin. r_{eff} = ¾ V/A [μm], where V is the particle volume and A the mean projected particle cross section area. F_{LW}(reff) = 1-exp(-δ_{lr} r_{eff}) and $E_{LW}(\tau c)$ = exp(-δ_{lc} τ_c). Other parameters are provided by [12, Table 1]: Kt = 1.953, TO = 152, δτ = 0.941, δ_{1r} = 0.21, δ_{1c} = 0.16, t_A = 0.879, Γ= 0.242, Aμ = 0.361, Bμ = 0.709, Cμ = 0.709, Fr = 0.512, δ_{SR} = 0.157, δ_{SC} = 0.157, δ'_{SC} = 0.23.

The crystal diameter, Optical Depth (τ), and Optical depth above the Contrail (τc) as the Contrail ages are set according to [14] and summarized in Table 2.

TABLE 2: Conditions for contrail persistence

Hour of Contrail Duration	Diameter (nm)	Optical Depth (τ)	Optical Depth Above Contrail (τc)
1	10	0.4	0.36
2	20	0.2	0.18
3	25	0.08	0.072
4	25	0.02	0.018
5	25	0.01	0.009

Shortwave Radiation Calculation:

$$RF_{SW}= -SDR\ (t_A-A_{eff})^2\ \alpha_c(\mu,\tau,r_{eff})E_{SW}(\mu,\tau_c)$$

SDR is calculated considering the SLR is the solar direct radiation in W/ m^2 and A_{eff} = RSR / SDR (reflected solar radiance / solar direct radiance). S_0 is the solar constant and μ defines the cosine of the solar zenith θ (SZA), θ is the *solar zenith angle,* α is the *solar elevation angle (*α = 90- θ), h is the hour angle, in the local solar time, δ is the current declination of the Sun, Φ is the local latitude.

The terms of the equations and values used are defined in Table 3.

TABLE 3: Equations and Values for calculation of RF_{SW}

$\alpha_c(\mu,\tau,r_{eff}) = R_c(\tau_{eff})[C_\mu + A_\mu R'C(\tau')F_\mu(\mu)]$
$\tau' = \tau F_{SW}\ (r_{eff})\ ,\ \tau_{eff} = \tau'/\mu$
$F_{SW}(r_{eff}) = 1 – F_r\ [\ 1\text{-exp}\ (\ -\delta_{sr}r_{eff})]$
$R_C(\tau_{eff}) = 1\text{-exp}(-\Gamma\ \tau_{eff}\ )$
$R'_C(\tau_{eff}) = \exp(-\gamma\ \tau_{err}\ )$
$F\mu(\mu) = [(1-\mu)^{B\mu} / (1/2)^{B\mu}\ ] -1$
$E_{SW}(\mu,\tau_c) = \exp\ (\delta_{SC}\tau_C – \delta'_{SC}\ \tau_{c,eff})$
$\tau_{c,eff} = \tau_c / \mu$
μ is cosine of the solar zenith angle = cos[(latitude$_{tr}$ /60) π/180]
$\mu = \cos(\theta) = SDR / S_0$

SDR = $\cos(\theta)*S_0$
S_0 = 1,361 Wm-2
δ is Declination Angle = -23.44° cos[360°/365 (N+10)], where N is number of day of year from January 1st (N=1) to December 31 (N=365).

Step 7: Estimate Fuel Burn

Fuel-burn for each flight is estimated for the original Cruise Flight Level and the adjusted Cruise Flight Levels. The Fuel-burn is calculated using EuroControl Base of Aircraft Data – Airline Performance Model (BADA - APM) tables [13]. The Nominal fuel flow for climb in kg/min is calculated by multiplying the specific fuel consumption by Engine Thrust (T). V_{TAS} is set to 266 knots for ascent above FL100 and to 276 knots for descent above FL100. Below FL100, V_{TAS} is set to 250 knots. For the Cruise phase, V_{TAS} is the Mach equivalent of 0.78 Mach. The Rate of Climb and rate of Descent is assumed to be at a constant 3° angle. The weight of the aircraft is determined by the average Empty Takeoff Weight plus a Fuel Weight estimated based on stage-length. The TOGW is constrained by the limits for the aircraft type in the BADA tables. The distance is estimated along the track of the trajectory and time is calculated based on the track data. All coefficients are derived from the BADA tables [13].

The next section uses this method to evaluates the effect on Net Radiative Forcing (NRF) and Fuel Burn (FB) for alternate Cruise Flight Levels.

RESULTS OF CONUS ANALYSIS FOR ALTERNATE CRUISE FLIGHT LEVELS

The analysis was conducted using one year of hourly atmospheric data (2015). A single day of flight trajectories were run for each different day of atmospheric conditions. The flight trajectories were selected from CONUS ADS-B data from 24,095 flights from June 20, 2016. Eligible flights had to include those flights with a complete trajectory and included both a departing and arriving airport within the CONUS. Any flight that did not present sufficient data points to provide a full trajectory when compared to its Great Circle distance was excluded. The Cruise Flight Level for each flight was determined by heuristics that eliminated short intermediate level-offs.

Total Daily Metrics

Daily Percent of Flights that Generated Contrails

For the baseline case with the flight's original Cruise Flight Level, the daily percentage of flights that generated contrails varied between a minimum of 1.3% and a maximum of 34.6% with a daily average of 15.1% and a daily median of 13.8% (Figure 7).

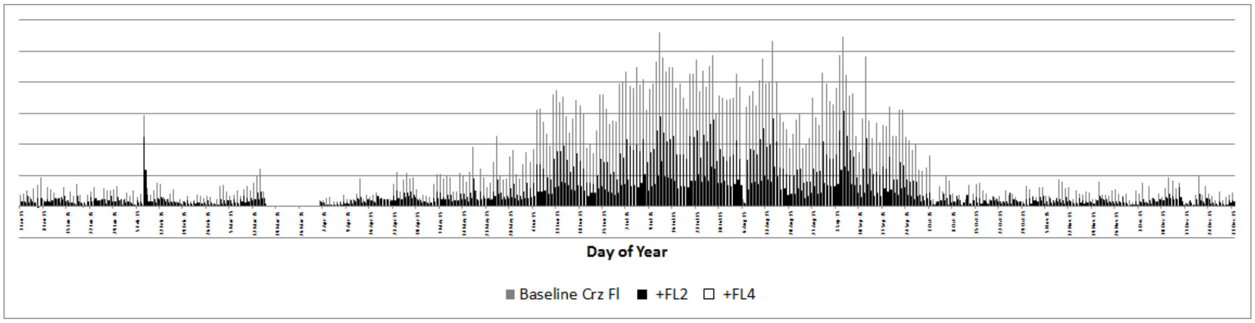

FIGURE 7: Daily % of the Flights that generated Contrails for one year of atmospheric data. Raising the Cruise Flight Level for contrail generating flights by 2000' and 4000' halves the percentage of flights that generate contrails.

Adjusting the Cruise Flight Level up by 2000' for those flights that generated contrails, decreased the average daily percentage of flights that generated contrails to a half of the baseline (from an average of 15.1% to an average of 7.1%). The daily range was now between a minimum of 1.3% and a maximum of 20.8% (Table 4).

Adjusting the Cruise Flight Level up by 4000' for those flights that still generated contrails with another 2000' increment, decreased the average daily percentage of flights that generated contrails to a quarter of the baseline (from an average of 15.1% to an average of 4.2%). The daily range was now between a minimum of 0.8% and a maximum of 10% (Table 4).

TABLE 4: Statistics for percentage of flights that generated Contrails for Original, +2000' and +4000' Cruise Flight Levels

	Baseline	+FL2	+FL4
MIN	1.3%	1.3%	0.8%
MEDIAN	13.8%	6.3%	3.8%
AVG	15.1%	7.1%	4.2%
MAX	34.6%	20.8%	10.0%
STD DEV	7.6%	3.4%	2.3%

Daily Contrail Along-Track Distance

Flights with their Original Cruise Flight Levels generated an average daily Contrail Along Track Distance (ATD) of 57,422 nautical miles. Increasing the Cruise Flight Level of the contrail generating flights by 2000' reduced the average daily Contrail Along Track Distance by 51% (Figure 8). Increasing the Cruise Flight Levels for those flights still generating contrails by another 2000' reduced the average daily Contrail Along Track Distance by 73%.

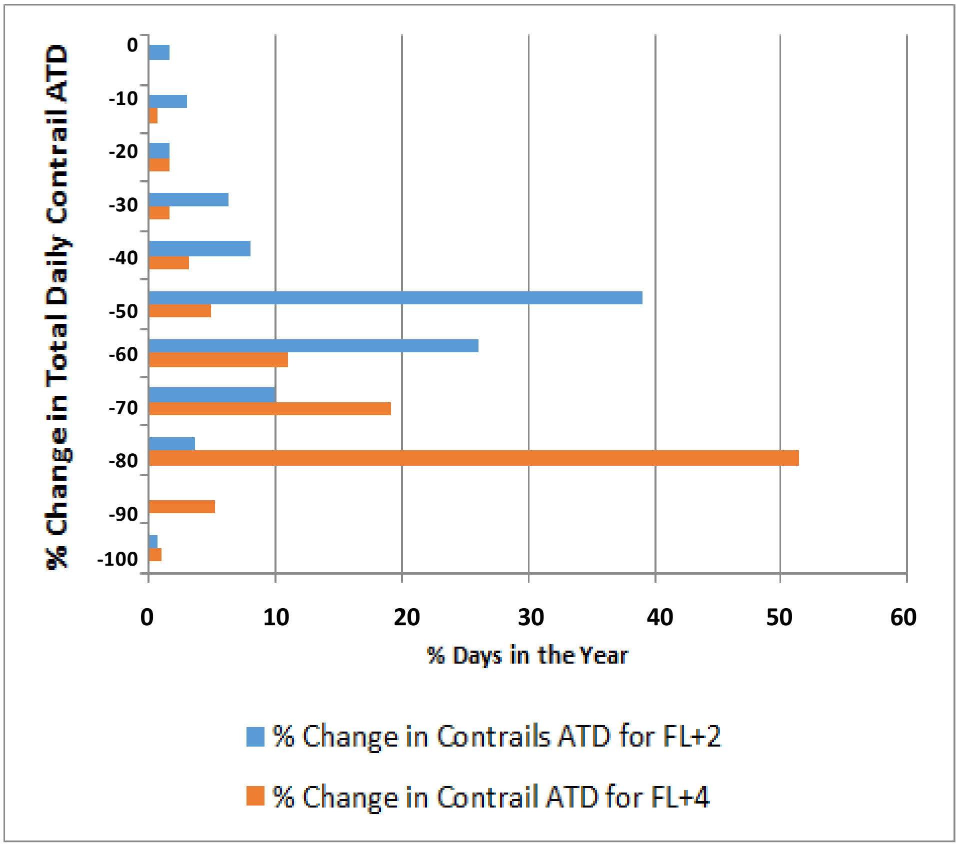

FIGURE 8: Percentage change in Contrail Along Track Distance with a 2000' and 4000' increase in Cruise Flight Level for those flights generating contrails.

Daily Total Fuel-Burn

As flights operated at higher Cruise Flight Levels they traded-off savings from lower Fuel Burn due to lower Drag, with the additional fuel required for the additional 2000' and 4000' climb and descent. The net effect was a marginal reduction in Daily Total Fuel Burn for flights using higher Cruise Flight Levels (Figure 9). This was a result of the lower Drag at higher Cruise Flight Levels particularly for flights with long range cruise. Note, the Summer months, with increased prevalence of Ice Super Saturated regions that required more flights to use higher Cruise Flight Levels, exhibited slightly lower daily total fuel burn.

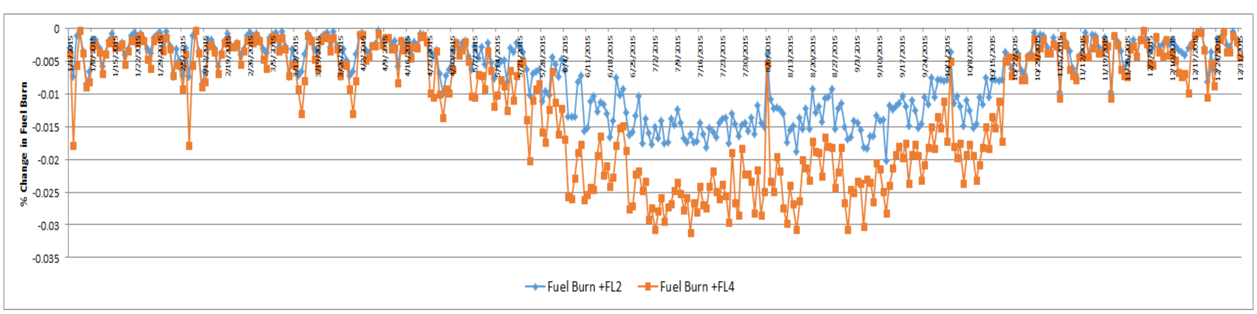

FIGURE 9: % change in Daily Total Fuel Burn for 2000' increment (blue) and 4000' increment (orange). Summer months, with increased prevalence of Ice Super Saturated regions that required more flights to use higher Cruise Flight Levels, exhibited greater reduction in fuel burn.

The average Daily Total Fuel Burn decrease was –0.7% for the 2000’ increment in Cruise Flight Levels for the flights that generated contrails at their original Cruise Flight Level (Table 5). The average Daily Total Fuel Burn decrease was –1.14% for the 4000’ increment in Cruise Flight Level for the flights that generated contrails even with the 2000’ increment in Cruise Flight Level.

A statistical test at 95% confidence interval for did not reject (i.e. accepted) the Null Hypothesis that there was no change in Daily Total Fuel Burn for going from the original to the 2000’ increment in Cruise Flight Level, and from the original to the 4000’ increment in Cruise Flight Level.

TABLE 5: Statistics for the Percentage Change in Daily Total Fuel Burn change from original to +2000’ Cruise Flight Level and to +4000’ Cruise Flight Level

Daily Total % Change	FB + FL2	FB +FL4
MIN %	-0.02%	-0.03%
MEDIAN %	-0.51%	-0.77%
MEAN %	-0.70%	-1.14%
MAX %	-2.02%	-3.11%
STD DEV %	0.55%	0.93%

Daily Total Net Radiative Forcing (NRF)

For the baseline case with the flights at the original Cruise Flight Level, the average Total Daily NRF was 7.08 mW/m2 with a Standard Deviation of 3.59 mW/m2. The use of higher Cruise Flight Levels to avoid creating contrails yielded a reduction in NRF (Figure 10).

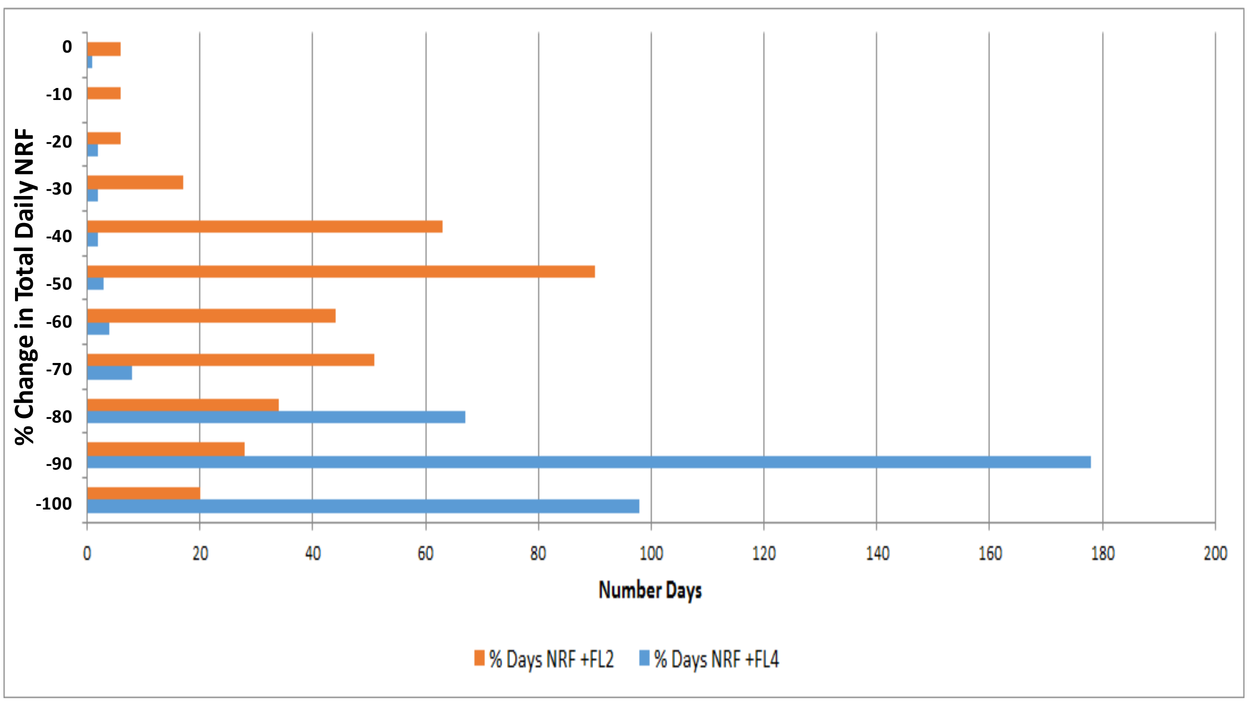

FIGURE 10: Percent Change in Daily Total NRF 2000’ increment (blue) and 4000’ increment (orange).

The average Total Daily NRF using a 2000' increment in Cruise Flight Level for those flights that would otherwise generate contrails at their original Cruise Flight Level yielded a -63% reduction in NRF (Table 6). The Total Daily percent change in NRF ranged from 0% to -100% depending on the confluence of the trajectories and the location of the ISS.

The average Total Daily NRF using a 4000' increment in Cruise Flight Level for those flights that would otherwise generate contrails even with a 2000' increment Cruise Flight Level yielded, a -92% reduction in NRF (Table 6). The Total Daily percent change in NRF ranged from -6% to 100% depending on the confluence of the trajectories and the location of the ISS.

TABLE 6: Statistics for the Percentage Change in Daily Total NRF change from original to +2000' Cruise Flight Level and to +4000' Cruise Flight Level

Daily Total % Change	NRF +FL2	NRF +FL4
MIN %	0%	-6%
MEDIAN %	-59%	-95%
MEAN %	-63%	-92%
MAX %	-100%	-100%
STD DEV %	21%	12%

A two-tailed t-test of the Baseline and the 2000' increment distributions for Total Daily NRF exhibited statistical significance at a 99% confidence interval. A two-tailed t-test of the Baseline and the 4000' increment distributions for Total Daily NRF exhibited statistical significance at a 98% confidence interval.

Summer-only Statistics

Seventy three percent (73%) of the total NRF is generated in the Summer months June, July, August and September. A program that mitigated contrails by Cruise Flight Level increments in the Summer months only, would capture 66% of the NRF total annual reduction from the 2000' Cruise Flight Level increment, and 93% of the NRF total annual reduction from the 4000' Cruise Flight Level increment.

CONCLUSIONS

Contrails generate a net warming on the Earth's temperature by blocking approximately 33% of outgoing Longwave radiation re-emitted by the Earth. Avoiding contrails would eliminate this "greenhouse effect" and not increase temperatures.

Policy makers and industry have asked what is the potential for mitigating contrails through operational changes in air traffic control and flight planning for the U.S.

Previous research using a representative single daily schedule for flights operating the U.S. National Airspace System (NAS) over 365 days of hourly atmospheric conditions identified that a maximum of 34% of the flights generated contrails on a given day [5, 15]. The daily average percent of flights was 15.1% with a median of 13.8%. The contrails were generated by flights in the mid-Atlantic and south-eastern United States as well as on the West-coast where the Ice Super Saturated regions are most prevalent. The Summer months exhibited approximately 3 times more contrails and Net Radiative Forcing than the rest of the year. The previous research also showed that the majority of flights with Cruise Flight Levels between FL340 and FL360 could avoid the ISS regions (and not generate contrails) with a 2000' or 4000' increment in Cruise Flight Levels.

This analysis provided a first-order measure of the potential benefits and costs of contrail avoidance in the contiguous US national Airspace System for a one day flight schedule across 365 days of hourly atmospheric data. The analysis evaluated the impact on NRF of a 2000' or 4000' increment in Cruise Flight Levels for all flights in the CONUS NAS that would generate contrails at their original Cruise Flight Levels.

The results were an average daily decrease of -63% decrease in NRF with a 2000' increment in Cruise Flight Level, and an average daily decrease of -92% decrease in NRF with up to a 4000' increment in Cruise Flight Level. These changes were considered statistically significant when compared to the original Cruise Flight Level at the 99% confidence interval.

These benefits in reduced NRF were at the potential cost of additional Fuel Burn. The difference in Fuel Burn for trajectories with the Original Cruise Flight Level and the incremental Cruise Flight Level was *not* statistically significant. The additional fuel required to climb/descend the additional 2000' or 4000' was overcome by the benefits of cruise at the higher altitude with lower Drag. This was especially true for flights with long duration cruise segments.

Limitations and Future Work

As noted, the formation of contrails and their impact on climate change is a complex, evolving science. Estimates of NRF are subject to uncertainty bounds estimated at 90% [3]. For a retrospective of confidence intervals of RF estimates of contrails see [1, Figure 7]. The models used in this paper are derived from the latest peer-reviewed scientific publications.

This analysis provided a first-order measure of the potential benefits and costs of contrail avoidance in the contiguous US national Airspace System. As such there are several ways to enhance the model, extend the analysis, and alternate concept-of-operations.

The model could be enhanced by taking into account the additional factors that could impact the use of higher Cruise Flight Levels. These include wind optimal routing, use of Cost Index, time impact on airline schedules for connecting flights and crews. The Fuel Burn calculation could also be enhanced with an expanded data-base of aircraft and engine types and a set of track data that had a higher percentage of equipment type records complete. Note: it is not anticipated that the fuel burn results would change dramatically, as the majority of the aircraft were matched with the data-base, and there were equal number of not-matched aircraft that had higher and lower fuel burns.

The analysis could be extended by performing the analysis using the specific day of aircraft track data. This analysis was conducted with a single representative day of flight track data to yield an analysis that did not confound atmospheric data with flight schedules.

There are also opportunities to perform analysis for alternate concepts-of-operations. For example, analyze the NRF impact of laying contrails directly on top of each other for flights on the same en-route airways. This would require changes to the RF model. Other mitigations take into account the shifting trajectories over existing, natural clouds, shifting trajectories to fly over surface areas with low albedo and away from high albedo surfaces, avoiding ISS regions with specific atmospheric properties that result in contrails with greater shortwave albedo and less longwave albedo (e.g. sea salt).

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