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Seasonal and Geographical Trends on Contrail Persistent Regions Over CONUS

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Abstract

Addressing contrail formation and avoidance will play a large part in the aviation sector's fight against climate change. Most research has focused on looking at contrail trends below 40,000 ft, the altitude range typically flown by commercial aircraft. The Sustainable Flight Demonstrator (SFD)'s Transonic Truss-Braced Wing (TTBW) has a cruise altitude of 43,000 ft, much higher than that of its replacement, the Boeing 737-Max. We use the Schmidt-Appleman criterion with weather data from the National Oceanic and Atmospheric Administration to take a closer look at contrails' seasonal and geographical trends over the Continental United States. We find that for the lower altitude range between 30,000 and 35,000 ft, as altitude increases there are more contrail persistent regions. However, the trend reverses after 40,000 ft to 50,000 ft and the area of contrail persistent regions decreases as altitude increases. Contrail seasonal and geographical dependence also depends on altitude, with lower altitudes having more contrail persistent regions in the winter and spring in the north and northwest. Higher altitudes have more contrail persistent regions during the summer and fall in the south. These results show how the TTBW would fly through less contrail persistent regions than the B737 and how to avoid the remaining regions.

Introduction

With the aggressive commitment made by the US aviation sector to reach net-zero carbon emissions by 2050 and the US Aviation Climate Action Plan, there has been a rising level of interest in contrails and their impact on global climate change. Contrails are line shaped clouds that form behind aircraft when flown at certain atmospheric conditions [1]. Water vapor emitted from aircraft cool and condense onto particulate matter in the local atmosphere. The particulate matter may be from the same aircraft or already present. Most contrails do not have a long time span, but in ice supersaturated regions (ISSR), persistent contrails may last up to 18 hours[4] and eventually merge with other clouds already present.

Contrails have a significant impact on global radiative forcing- in 2018, contrail cirrus clouds contributed 111 (high and low estimates of 33 and 189) mWm^{-2} to global radiative forcing, as compared to 34 (high and low estimates of 31 and 38) mWm^{-2} from CO_2 with a 95% confidence interval [6]. However, the warming effects from contrails are more temporal than those from CO_2 and are contained to localized areas. Regional atmosphere, seasons, and time of day all have a large impact on contrail formation and consequence. Thus, in addition to aircraft technology development, air traffic rerouting is an area that is being widely considered as a potential solution for contrail prevention. One such study from Teoh et al. [8] looked at diverting less than 2% of the fleet over the Japanese airspace above or below contrail persistent regions to reduce contrail energy forcing by 59% for a 0.014% increase in fuel consumption.

The Electrified Powertrain Flight Demonstration (EPFD) and Sustainable Flight Demonstrator (SFD) projects aim to demonstrate the implementation of two distinct sustainable aircraft concepts with a predicted entry into service in 2035. In particular, the SFD Transonic Truss-Braced Wing (TTBW) represents the next generation narrow body single aisle aircraft and targets to replace the currently flying Boeing 737-MAX (B737). The B737, like many commercial aircraft, generally flies at altitudes of 30,000 - 40,000 ft- a significantly lower altitude than the TTBW's target cruise altitude of 43,000 ft. Thus, making the same assumptions for the TTBW as those from current commercial aircraft to conduct contrail avoidance would be ill advised, seeing that the TTBW will be flying under very different atmospheric conditions.

Historically, contrail trends have been most often looked at over Europe and at the lower altitudes flown by most currently flying commercial aircraft. Dischl et al. [2] studied at the seasonal variation in persistent contrails above Europe at around 30,000 – 39,000 ft. Minnis et al [7] investigated contrails forming over select locations in the continental United States (CONUS). Since the work was conducted using observed contrails, the data is sparse and only shows contrails that were formed due to the aircraft from that generation. Contrail patterns at higher altitudes, where the TTBW will fly at, and over the entirety CONUS are not well understood.

In this paper, contrail patterns over CONUS have been analyzed to identify any geographical or seasonal trends at altitudes between 30,000 and 50,000 feet. By looking at this wider region, we hope to identify the contrail hotspots for next generation aircraft and prevent air traffic over-management for future implementations of contrail avoidance rerouting.

Methods and Data

Schmidt-Appleman Criterion

The main methodology used in this paper to assess persistent contrail regions is the Schmidt-Appleman criterion along with ice super-saturation regions (ISSR) for contrail persistence[3]. The Schmidt-Appleman criterion is a widely used model to find the threshold atmospheric conditions that would allow for contrail formation. If the atmosphere an aircraft flies through has a low enough temperature with high humidity, a contrail is formed due to liquid saturation[5].

The threshold temperature is given by the equation

$$T < T_{contr} = -46.46 + 9.43ln(G - 0.053) + 0.72ln^2(G - 0.053)$$

G is the slope of the isobaric mixing line

$$G = \frac{c_p p}{\varepsilon} \frac{EI_{H_2O}}{(1-\eta)Q}$$

where c_p is the specific heat capacity of air, p is the ambient air pressure, ε is the molecular mass ratio of water and air, EI_{H2O} is the emissions index of water, η is the propulsive efficiency of the aircraft engine, and Q is the combustion heat of the fuel used.

The relative humidity with respect to water, RH_w, must be greater than the critical value r_{contr}. r_{contr} can be found using the isobaric mixing line slope, temperature, the threshold temperature, and water vapor pressure ratio $e^{liq}{}_{sat}(T)$. The condition that RH_w must be lower than 100% is added to the Schmidt-Appleman criterion in this paper since RH_w at 100% indicates a cloud is already present.

$$1 > RH_w > r_{contr} = \frac{G(T - T_{contr}) + e_{sat}^{liq}(T_{contr})}{e_{sat}^{liq}(T)}$$

$e_{sat}^{liq}(T)$ is given by

$$e_{sat}^{liq}(T) = 6.0612exp(\frac{18.102T}{249.52 + T})$$

Most contrails don't last longer than 10 minutes and have a small climate impact [1]. However, persistent contrails formed in ISSR last for hours and contribute more radiative forcing. ISSRs occur when the relative humidity to ice RH_i is greater than 100%.

$$RH_i > 1$$

RH_i can be found using RH_w and temperature

$$RH_i = RH_w \frac{6.0612exp(18.102T/(249.15 + T))}{6.1162exp(22.577T/(273.38 + T))}$$

For the purposes of this paper, only persistent contrail regions are considered. The Schmidt-Appleman criterion in ISSR is evaluated at each spatial datapoint at specified time intervals in 2018. Constant parameters used are listed in Table 1.

Table 1: Parameters held constant to calculate the Schmidt-Appleman criterion

Parameter	**Value**
EIH_2O	1.25
C_p	1004 J Kg^{-1} K^{-1}
η	0.3
Q	42000000 J Kg^{-1}
ε	0.622

Meteorological Data

The National Oceanic and Atmospheric Administration (NOAA) publishes hourly atmospheric data made from a numerical forecast model for public use. For this paper, temperature and RH_w Rapid Refresh (RR) data from 2018 at altitudes 30,000, 35,000, 40,000, 45,000, and 50,000 ft are used. RR has a horizontal spatial resolution of 13 km, vertical isobaric pressure level resolution of 25 hPA, and one hour temporal resolution. NOAA covers the CONUS region with longitude and latitude data of -139.9° to -57.3° and 16.2° to 59.0° respectively. Several days and hours are skipped during analysis due to missing weather data and are listed in Table 2.

Table 2: Dates and Times of Missing RR Data

Date	Time (UTC)
01/13/2018	02:00 - 23:00
01/14/2018	00:00 - 20:00
01/18/2018	10:00 - 20:00
11/03/2018	4:00

Results

Contrail persistent regions over CONUS are calculated using the Schmidt-Appleman criterion with NOAA RR data as described in Section 3. To view temporal trends throughout the year, total persistent area is summed from data points taken every 3 hours for every other day. Datapoints are filtered through a Savitzky-Golay filter for trend clarity, and the plotted results are shown in Figure 1.

At lower altitudes, particularly at 30,000 and 35,000 ft, the trends for contrail persistent regions follow the observation that contrails decrease over CONUS in the summer months [7]. Europe seems to follow this trend as well [2]. However, as the altitude increases, the trend flips, and the winter and spring months have a very small amount of persistent contrail regions while the summer months have a significant increase. It is noticeable that total contrail persistent region area over the entire year at higher altitudes (45,000 and 50,000 ft) is less than that of the lower altitudes (30,000 and 35,000 ft). Only during the summer do the higher altitudes have a larger area of contrail persistent regions. This is mainly caused by the colder temperatures at higher altitudes. Lower altitude regions usually do not get cold enough to create contrails during the summer and thus contrail persistent regions drop off. At higher altitudes, the temperature remains cold enough for contrail formation, and persistent contrail formation becomes mainly restricted by a low RH_i unsuitable for ice super-saturation.

The effects of seasonality on geographic location and day and night cycles are observed as well. The average sunrise and sunset times from the east and west coast are taken to set the day and night times. Dates and times used are shown in Table 3.

Contrail persistent regions over CONUS in 2018 at 30,000 to 50,000 ft are shown in Figures 2 through 5. At the lower altitudes there are more contrail persistent regions overall, with a higher concentration in the northern section of CONUS. There is a particularly high concentration in the northwest section during spring and winter. The formation of these regions is driven by the temperature threshold, where only northern regions are cold enough to sustain persistent contrails. The RH_w is generally lower than the critical relative humidity r_{cont} in the south, also contributing to less contrails in southern lower altitudes. However, as the altitude increases, the contrail persistent regions become sparser and shift towards the south, with the summer and autumn seasons having more contrail persistent regions covering CONUS territory due to a constraint in RH_i.

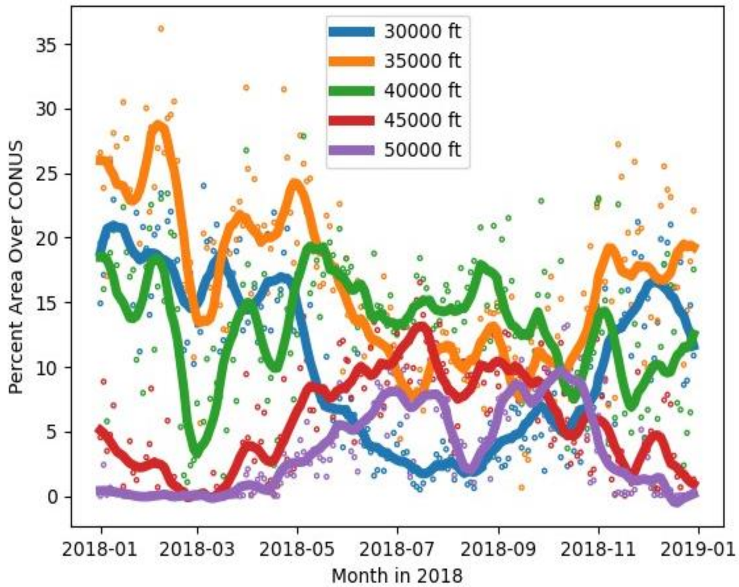
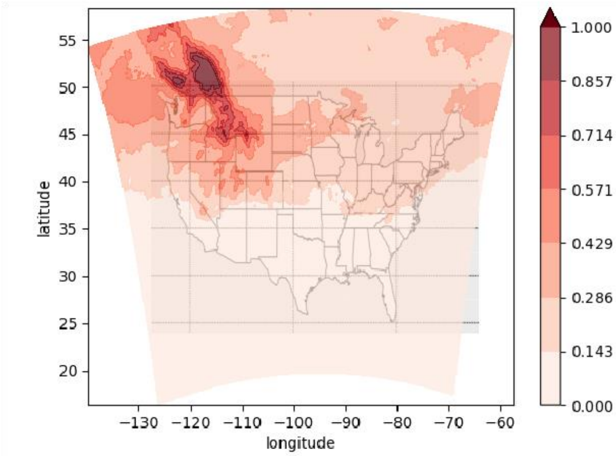


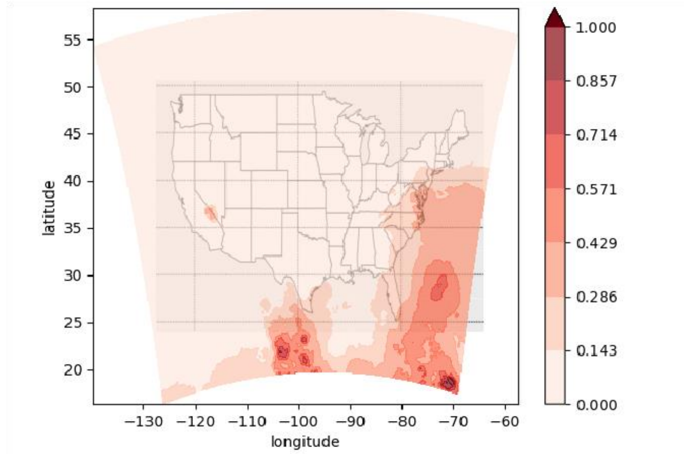
Figure 1: Percent of CONUS covered by persistent contrail regions through 2018, split by altitude

Table 3: Date and Day/Night Time for Each Season

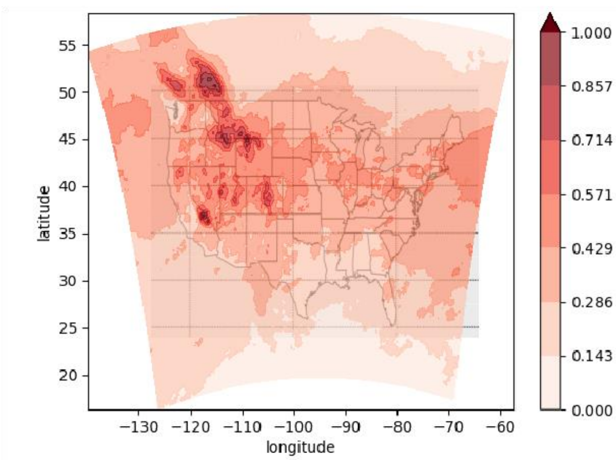
Season	**Date**	**Day Time**	**Night Time**
Spring	03/21/18 - 06/21/18	05:30 - 19:30	19:30 - 05:30
Summer	06/22/18 - 09/22/18	05:30 - 19:30	19:30-05:30
Autumn	09/23/18 - 12/21/18	06:30 - 18:30	18:30 - 06:30
Winter	01/01/2018 - 03/20/18, 12/22/18 - 12/31/18	06:30 - 18:30	18:30 - 06:30



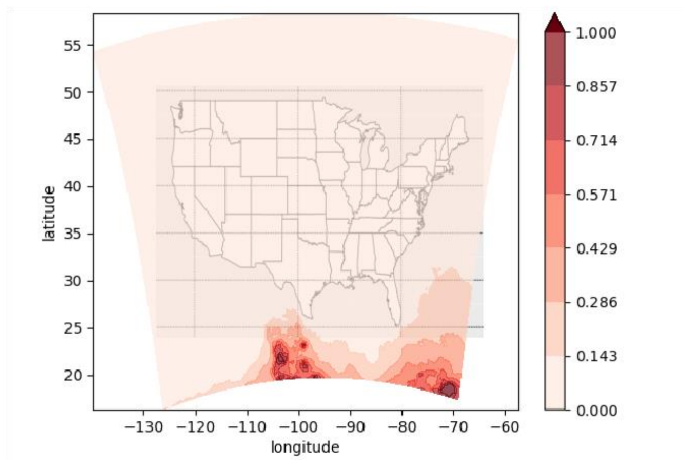
(a) 2018 Spring, FL 300



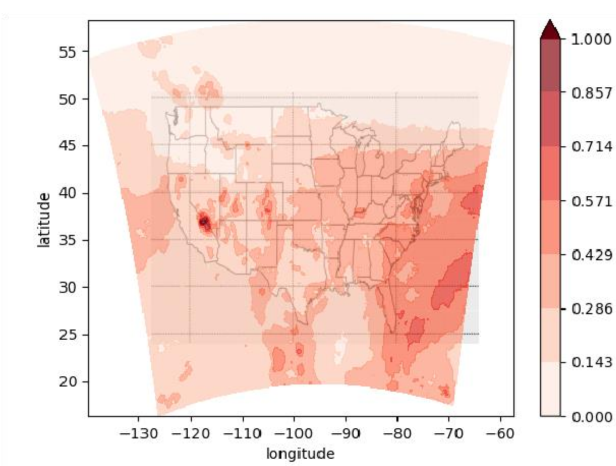
(d) 2018 Spring, FL 450



(b) 2018 Spring, FL 350

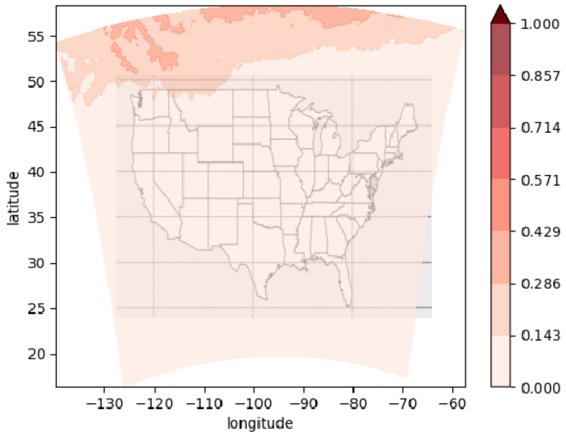


(e) 2018 Spring, FL 500

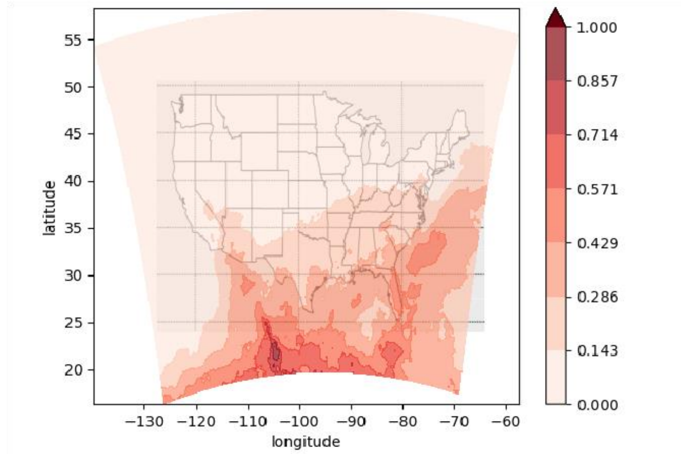


(c) 2018 Spring, FL 400

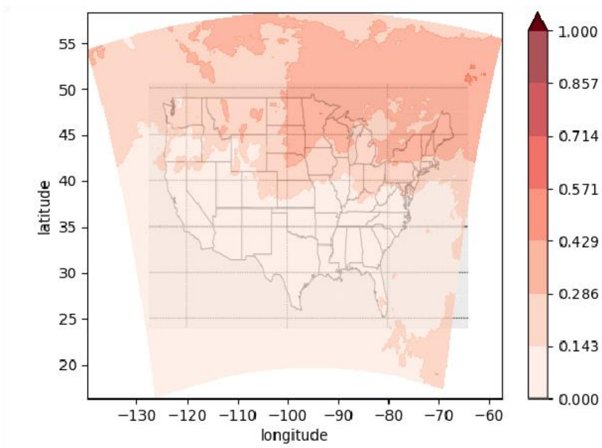
Figure 2: Contrail persistent regions over CONUS at flight levels 300-500 during spring, normalized. Darker regions indicate more contrail persistent region formation over the year.



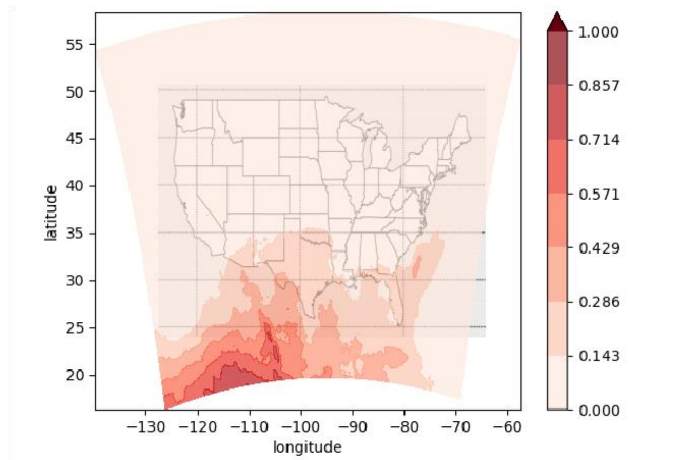
(a) 2018 Summer, FL 300



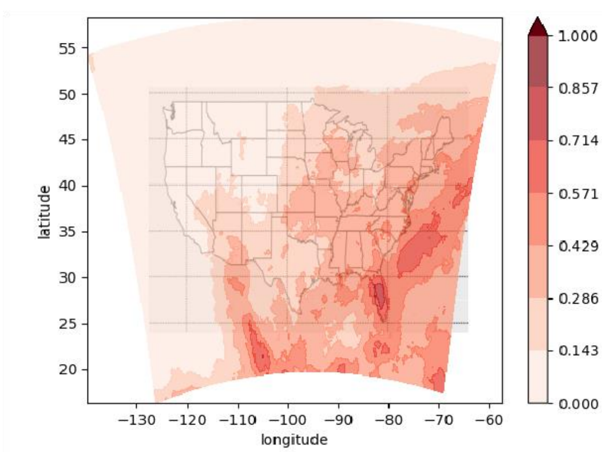
(d) 2018 Summer, FL 450



(b) 2018 Summer, FL 350

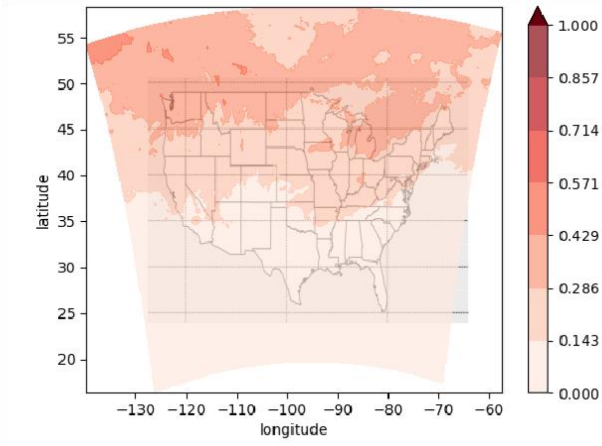


(e) 2018 Summer, FL 500

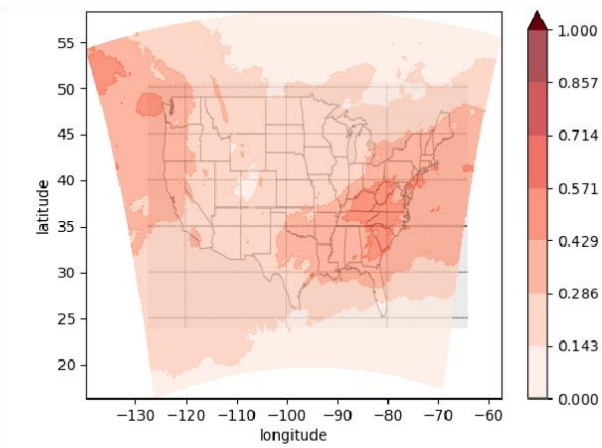


(c) 2018 Summer, FL 40

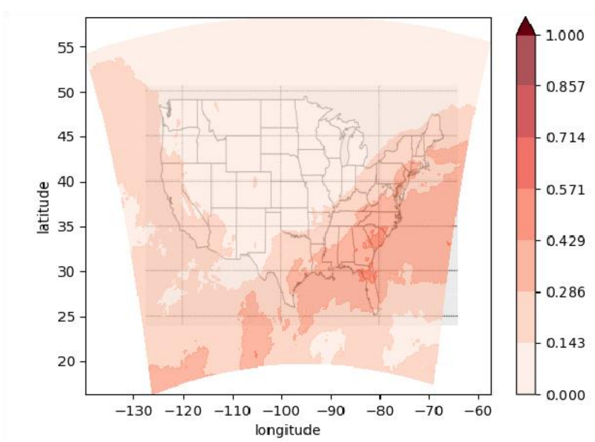
Figure 3: Contrail persistent regions over CONUS at flight levels 300-500 during summer. Darker regions indicate more contrail persistent region formation over the year



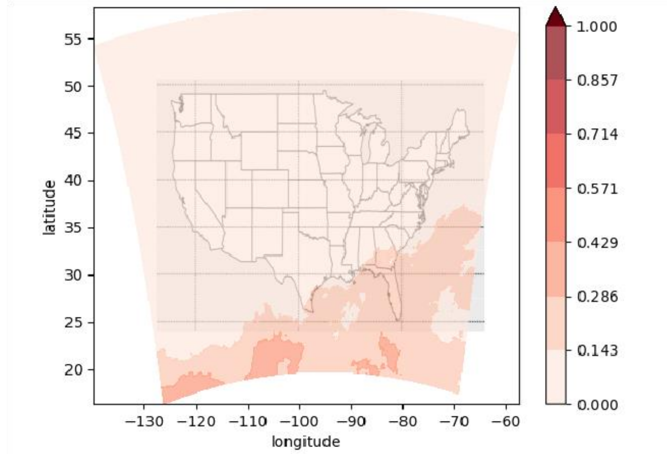
(a) 2018 Autumn, FL 300



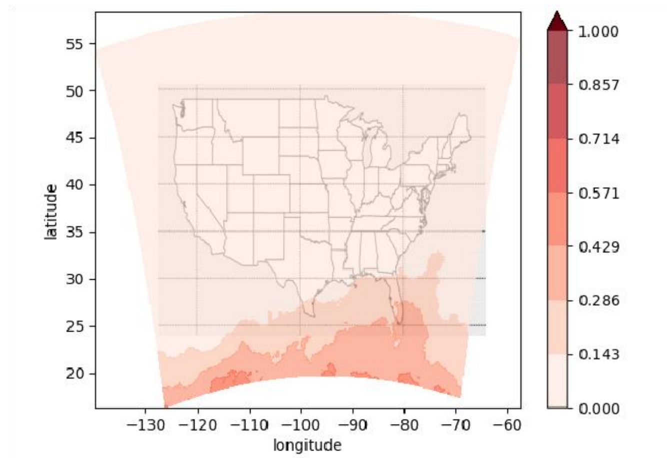
(b) 2018 Autumn, FL 350



(c) 2018 Autumn, FL 400

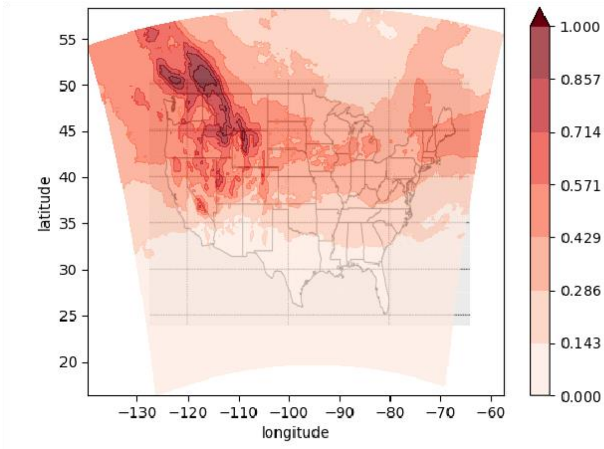


(d) 2018 Autumn, FL 450

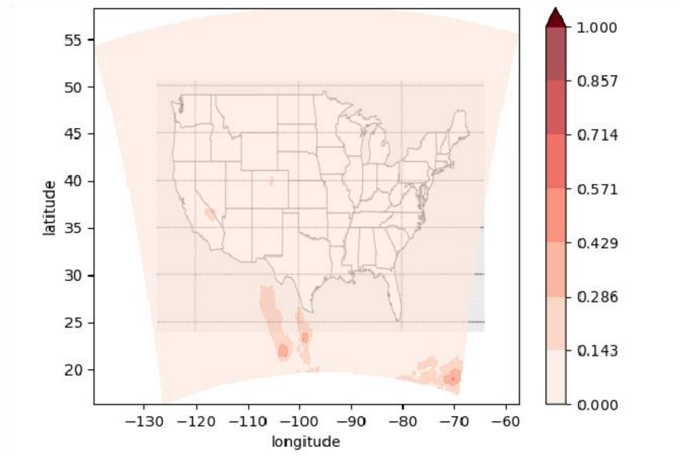


(e) 2018 Autumn, FL 500

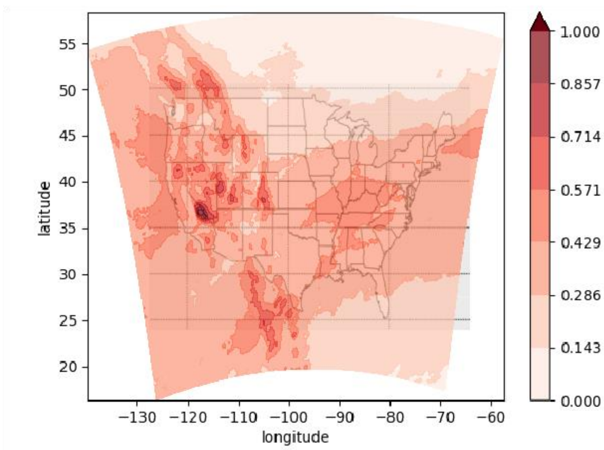
Figure 4: Contrail persistent regions over CONUS at flight levels 300-500 during autumn. Darker regions indicate more contrail persistent region formation over the year



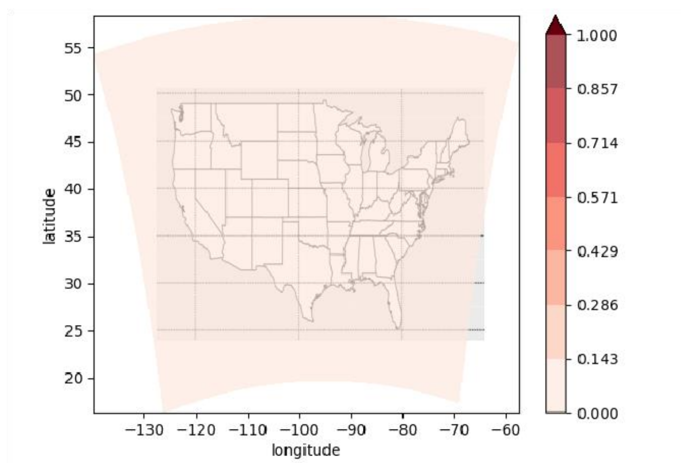
(a) 2018 Winter, FL 300



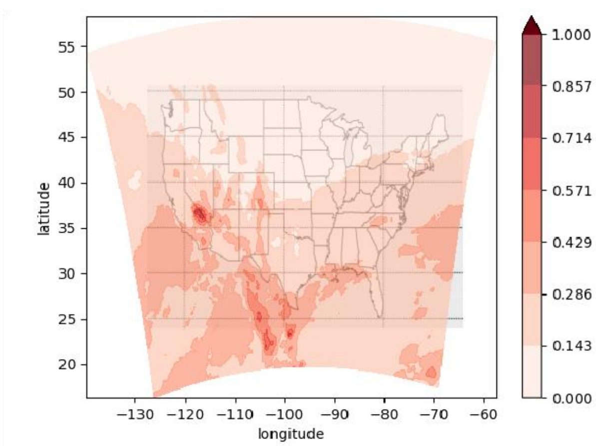
(d) 2018 Winter, FL 450



(b) 2018 Winter, FL 350



(e) 2018 Winter, FL 500



(c) 2018 Winter, FL 400

Figure 5: Contrail persistent regions over the CONUS at flight levels 300-500 during winter. Darker regions indicate more contrail persistent region formation over the year

Differences in day and night contrail persistent areas are analyzed, but no new noticeable trends are observed, as shown in Figure 6.

The effect in increasing the propulsive efficiency is also looked at. While a standard 0.3 propulsive efficiency for gas turbine driven engines is used for all analysis, the TTBW has a predicted propulsive efficiency of around 0.376. However, increasing the propulsive efficiency did not have an impact on the overall seasonal or altitude trends, as shown in Figure 7.

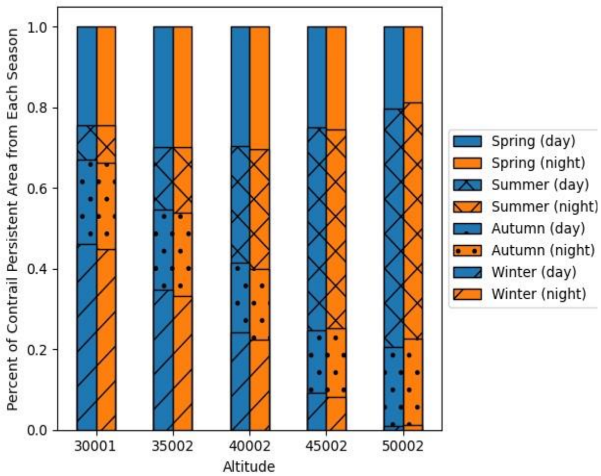


Figure 6: Comparison of Percent of Contrail Persistent Area over CONUS for each season for day and night

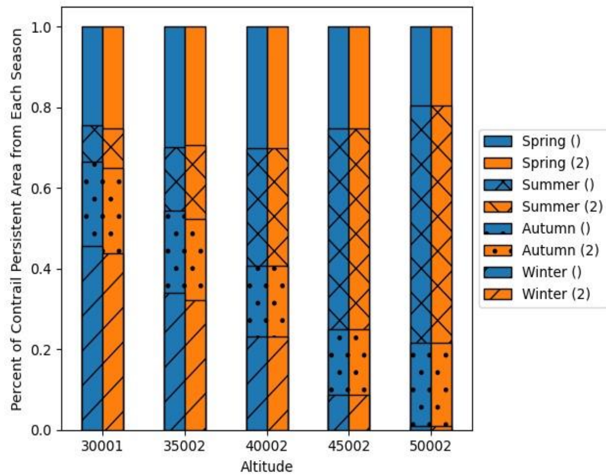


Figure 7: Comparison of Percent of Contrail Persistent Area over CONUS for each season for propulsive efficiency of 0.3 and 0.376

Summary and Future Work

This paper looks at the seasonal and geographical trends of contrail persistent regions 30,000 to 50,000 ft above CONUS. NOAA rapid refresh data is used with the Schmidt-Appleman criterion and ice super-saturation to determine contrail persistence.

Looking at the trends in contrail persistent regions over CONUS, we see more contrail persistent regions are created as altitude increases, peaking in the spring and winter months. The trend flips after 40,000 feet and the formation of contrail persistent regions decrease as altitude increases further. The spring and winter months have less contrail persistent regions than the summer and autumn months at these higher altitudes. These trends are determined by constraints in humidity and temperature and seem to focus on different geographical locations above CONUS. The lower altitudes have more contrail persistent regions overall but particularly in the north and northwest, while the higher altitudes have more in the south.

The B737 aircraft typically cruises at around 30,000 to 40,000 ft. At this altitude range, a significant portion of CONUS is covered in contrail persistent regions. The TTBW's preference towards higher cruise altitudes of allows it to avoid more contrail persistent regions over the entire year than the B737. For further contrail avoidance, air traffic control within CONUS would only need to focus on redirecting the TTBW around contrail persistent areas in the south and could entirely avoid redirecting the aircraft in the autumn and winter months.

The Schmidt-Appleman criterion and the results found are dependent on the reliability of the weather data available. While temperature forecasts are fairly reliable, relative humidity is much more difficult to predict [9][10]. It is possible that the discovered trends fall apart when a large uncertainty in weather data is introduced. It is also possible that the results only appear in 2018, and that contrail persistent regions in other years follow different patterns. Further analysis needs to be done on the sensitivity of the results to weather prediction and if the trends are repeatable for other years.

To take a closer look at the difference in contrail generation between the TTBW and B737, an ongoing study replaces B737 flights from the past with the TTBW using the NAS Digital Twin (NDT)[11]. NDT is an environment that simulates past, current, and future airspace operations. NDT uses the Schmidt-Appleman criterion as well but is being expanded to use the methodologies from the Contrail Cirrus Prediction Tool (CoCip) from DLR through pycontrails, a python package for contrail modeling.

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