DESIGN OF ICE SUPER SATURATED REGION (ISSR) VISUALIZATION TOOL FOR CONTRAIL PLANNING

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Abstract

Hot exhaust from jet airliners generate condensation trails when the appropriate atmospheric conditions exist. These high altitude "clouds" reflect 23% of incoming shortwave radiation back into space, but also reflect 33% of outgoing longwave radiation back to Earth. In this way, anthropogenic (i.e. human made) contrails have a net warming effect. Under the auspices of future government regulations, airlines could earn traffic flow management slot prioritization credits for flying flight plans that lay persistent contrails in the morning (to block incoming shortwave radiation) and avoid laying persistent contrails in the evening (to allow longwave radiation to escape).

This paper describes a method for processing publicly available weather forecast data to identify the location of Ice Super Saturated Regions where persistent contrails will form. The ISSRs statistics and a 3-D visualization of the ISSR over the CONUS are provided. The implications of this information and the limitations of the method are discussed.

Introduction

Jet airliners generate engine exhaust that is placed directly in the Troposphere. Condensation trails (i.e. contrails) occur when the hot exhaust from jet engines mixes with the cold low pressure atmosphere. The hot water vapor contained in the exhaust condenses and freezes on particles left by the engine creating an artificial cloud behind the aircraft.

These human-made clouds are equivalent to Cirrus clouds, except they are generated by human activity (i.e. anthropogenic). The Intergovernmental Panel on Climate Change (IPCC) estimated that contrails covered 0.1% of the Earth's surface and projected a growth of 5% per year until 2015 [1], [2].

These high altitude thin clouds are highly transparent to incoming shortwave radiation from the Sun. 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 (49%) or be absorbed by the atmosphere (23%). These clouds also absorb a portion of the outgoing longwave radiation, and reflect a fraction back to the surface (33%) adding to the shortwave energy. The overall effect of contrails is to enhance atmospheric greenhouse warming.

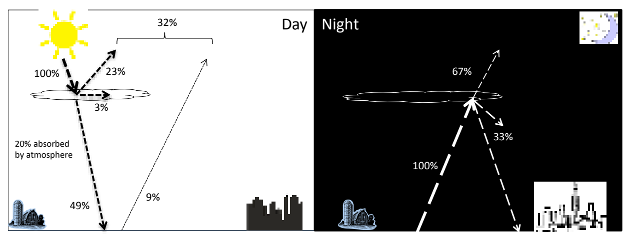


Figure 1: Effect of contrails on incoming shortwave radiation and outgoing longwave radiation

The *presence* of contrails in daylight hours has a net positive effect on greenhouse warming by reflecting incoming shortwave radiation back into space. The *absence* of contrails during night time hours has a net positive effect on greenhouse warming by allowing the outgoing longwave radiation to escape into outer space.

As part of Climate Change mitigation initiatives, a future scenario could see the government incentivize airlines to lay/avoid laying contrails by offering credits that could be used in Traffic Flow Management Initiatives for capacity constrained airspace and airports. Under these circumstances, each airline could earn credits for contributing to persistent contrails in the day-time and by avoiding persistent contrails in the evening and night [3], [4]. To facilitate this type of flight planning, the time and location of forecast Ice Super Saturated Regions (ISSR) and the capability to inventory the contrails is required.

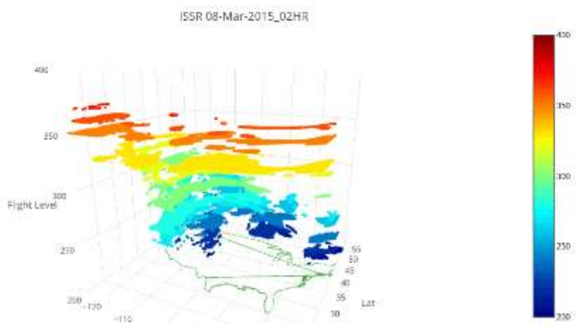


Figure 2: 3-D visualization of ISSR for Contiguous US

This paper describes the design of Ice Super Saturated Region (ISSR) Visualization Tool for Contrail Planning. Section 2 provides an overview contrails and their effect on global warming. Section 3 describes process for extracting ISSR data from publicly available weather data and transforming it into 3-D visualization of ISSR. Section 4 provides some examples. Section 5 discusses the implications of this technology.

Contrails, Global Warming

Contrails are generated when the exhaust from jet engines mixes with the cold low pressure atmosphere. The hot water vapor contained in the exhaust condenses and freezes on particles left by the engine creating an artificial cloud behind the aircraft.

These human-made clouds are for all effect Cirrus clouds. They are high altitude -greater than 20,000 ft. - thin clouds which are 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 absorb a portion of the outgoing longwave radiation, and reflect a fraction back to the surface adding to the shortwave energy. The overall effect is therefore to enhance atmospheric greenhouse warming [1].

In the 1999 report the Intergovernmental Panel on Climate Change (IPCC) estimated that contrails covered 0.1% of the Earth's surface and projected a growth of 5% per year until 2015 [2]. During many years the effect contrails could have had been dwarfed by the effect of greenhouse gases emitted by aircrafts. In recent years contrails have gained some attention and in the 2013 report "Anthropogenic and Natural Radiative Forcing" [5] the IPPC revised its estimates and "elevated the potential impact of contrails."

Contrail Statistics

Two statistics are used to quantify the presence of ISSRs: (1) % volume of the ISSR in the CONUS airspace, and (2) the % area covered by the ISSR at each Flight Level [5].

$$\% \, FL \, Area \, (i) = \frac{Count \, of \, ISSR \, Grids * Grid \, Area}{Total \, Area \, of \, CONUS \, at \, FL \, (i)}$$

$$\% \, CONUS \, Volume = \frac{Count \, of \, ISSR \, Blocks * Block \, Area}{Total \, Volume \, of \, CONUS}$$

The % of Flight Levels with ISSR for each month in 2015 is shown in Figure 3. Flight Levels 320 and 340 experience the highest % of ISSRs. Seasonal effects are evident. ISSRs are present throughout the year, however they reach their peak at FL 340 at 30% area in the summer months (June to September).

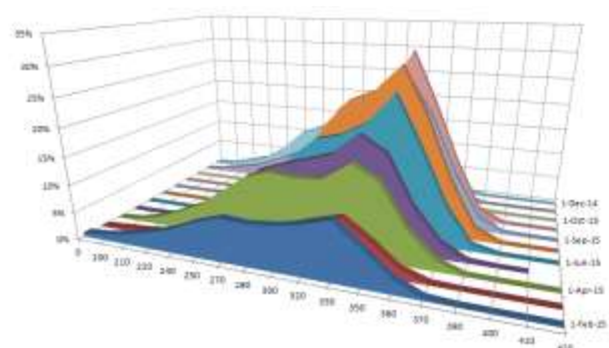


Figure 3 Percentage of ISSR Coverage in the US Airspace 2015 [5]

An analysis of the frequency of ISSRs by altitude during the month of August 2015 is shown in Figure 4. The highest presence can be seen from Flight Levels 280 to 380. The most frequent occurrence is at Flight Level 340.

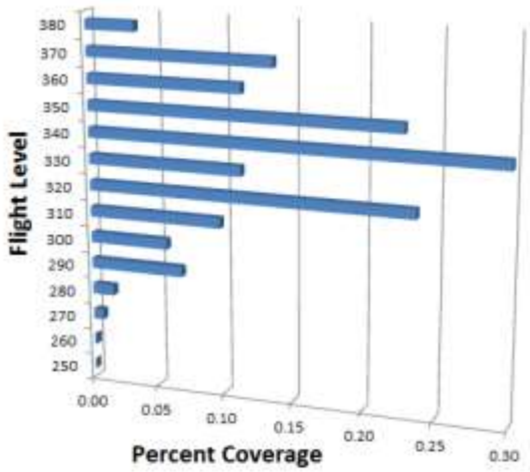


Figure 4: Average ISSR coverage by Flight Level in August 2015 (%) [5]

Table 1 ISSR frequency by Flight Level (Percentage of total air space) [16]

Flight Level	Nov-14	Dec-14	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15
380	0	0	0	0	0	0	2	4	4	4
370	2	1	0	0	2	3	9	13	14	13
360	1	1	0	0	2	2	9	12	11	12
350	5	6	3	2	6	9	18	23	23	19
340	10	14	8	6	15	17	26	28	30	26
330	2	3	2	2	4	7	11	11	11	11
320	12	22	15	12	21	24	24	26	24	23
310	8	11	9	5	10	10	9	9	10	7
300	4	6	3	2	5	7	5	5	6	4
290	8	13	10	5	14	15	9	5	7	6
280	3	7	4	2	7	7	4	1	2	2
270	4	8	5	3	9	5	3	1	1	2
260	2	3	2	1	3	2	1	0	0	1
250	3	5	4	2	4	1	0	0	0	1
240	2	2	2	1	2	1	0	0	0	0
230	1	1	1	0	1	0	0	0	0	0
220	1	1	1	0	1	0	0	0	0	0

Table 1 provides a heat map combining the effect of the seasonality along with Flight Level. FL 320 – 340 exhibit ISSRs all year round. In the winter and spring, when ISSRs do occur they tend to be lower (i.e. FL 220 – 350), than in the summer (i.e. FL 270 – 380).

Mitigating Effects of Contrails

Research for options for contrail generation mitigation includes: (1) technological developments (e.g. a new engine and airframe technologies), and (2) operational changes (e.g. continuous decent approaches). Kaiser [6] analyzed generating contrails as an exchange a tradeoff between contrail formation and fuel burn and its CO_2 emissions. Gierens [7] reviewed various strategies for contrail avoidance. Mannstein [8] proposed a strategy to reduce impact by small changes in individual flight altitudes. Chen N, Sridhar, B**.** [9] suggested a strategy to reduce persistent contrail formation while accounting for extra emissions and air space congestion. Campbell [10] focused on reducing contrails via fuel burn reduction. Fichter [11] describes a method using onboard contrail detection system and fight rerouting. Others limit the flight altitude by introduce a maximum altitude restriction policy.

In airline operations, Cruise flight levels are chosen to optimize between the duration of the flight and to minimize fuel burn. Changes in along-track distance and or flight levels to avoid contrails will trade increases in fuel burn and CO_2 emissions with reduced net radiative forcing from contrails. This type of trade-off has been studied Kaiser (2012) [6], Sridhar et. al. (2013) [12], Chen (2012) [13], Gao & Hansman (2013) [14].

Using Contrails to Fight Global Warming

Under a future scenario in which governments address the impact of contrails on climate change the following concept of operations has been proposed [17], [3]: Flights will: (1) intentionally seek ISS regions and lay contrails in the morning to take advantage of the albedo benefits of the clouds to reflect incoming shortwave radiation, and (2) flights would actively avoid ISS regions to prevent the formation of contrails in the late afternoons and evenings to maximize the release of outgoing longwave radiation.

Airlines could earn credits that could be sold, swapped or used by the airline during Traffic Flow Management Initiatives to gain priority for slot allocations in capacity limited airspace and airports.

To perform this function airline operation centers (AOCs) would need to know the current and future location of ISSRs.

The time of day, and tradeoff between CO2 emissions from excess fuel burn by seeking/avoiding contrails, are topics that are being investigated.

Process for Generating Statistics and 3-D Visualization of ISSRs from Weather Data

Contrails in general can be generated under several conditions, however for the purpose of the con-ops described above this process is limited to Persistent Contrails. The formation of persistent contrails requires specific weather conditions: temperature at or below –40°C (233.15 K) and a Relative Humidity of 100%. The longer and larger the coverage of the ISSR the larger the contrail will be and the longer it will persist, increasing its effect. Hence the interest to better understand the existence and coverage of ISSRs.

The following process describes a method to identify and visualize the Ice Saturated Regions. To identify the ISSRs NOAA Rapid Refresh Products (RAP) files are used. The files provide weather indicators under a Lambert Conformal projection with a 13-km resolution. The process uses a prebuilt database extracted from the weather files identifying regions where contrail formation requirements have been met.

Generation of the visualizations will require dynamically building queries and extracting data as well as 3D graphical capabilities. To facilitate the process the visuals are generated in R [15].

The process for generating the 3-D ISS region visualizations is composed of the following steps summarized in Figure 5:

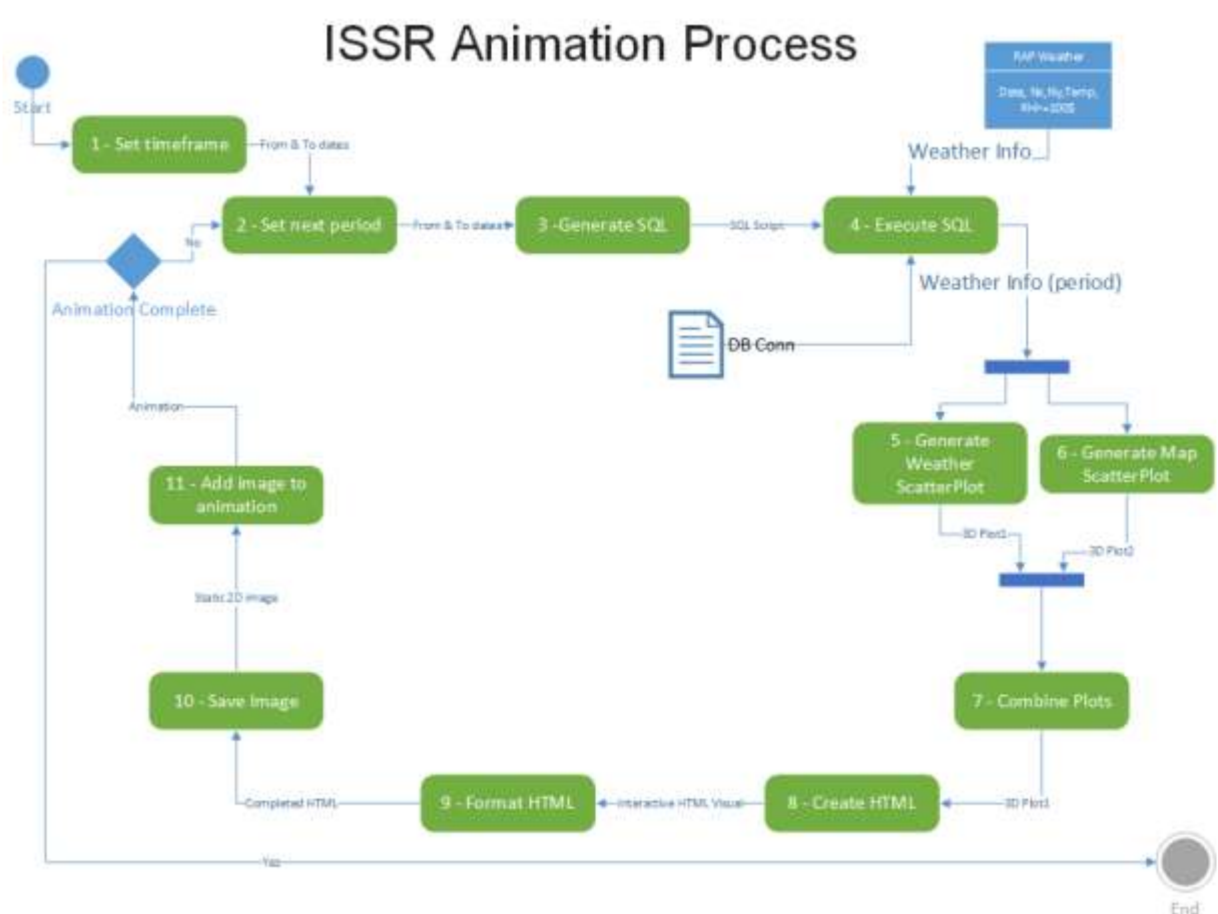


Figure 5: Process for generating ISSR 3-D visualization

1. Set timeframe

   This step will set parameters for a start and end date for the process and establish the number and duration for each visualization.

2. Set Next Period

   Initialize "Next period" to start date, or Increase using the current period and duration.

3. Generate SQL

   Build SQL to retrieve weather data for next period. The query will need to take into account the fact that the database contains exclusively ISSR positive points. Since all these points already indicate the existence of a saturated region the process is reduced to restricting the date and time of interest and then aggregating by flight level. Additionally to manage the size of the data visualizations are limited to frequent flight levels. For this exercise FL 200 to 400.

4. Execute SQL

   Connect to database, run query and retrieve weather data. For this implementation the execution step took place via a JDBC connection.

5. Generate Weather Scatter plot

   The "image" of the ISSR is generated by creating a 3D scatterplot of the returned points. The data frame is read as vectors creating the entire plot at once where x = [Lon]; y = [Lat] and z = [Flight Level]. At the time the scatter plot is generated the plotted points create a series of layered "cloud-like" surfaces at each flight level. Flight levels are color coded to facilitate identification.

6. Generate Map Scatter plot

   An outline of the United States is graphed on flight level 200 of a second 3D scatterplot.

7. Combine Plots

   Plots 5 and 6 are combined. The final plot is limited to flight levels 200 – 400 setting the map as the base of the visual.

8. Create HTML

   Generate the HTML for the plot created on step 7.

9. Format HTML

   The visuals are generated as HTML interactive files that can be rotated and zoomed into the desired view. This step will set the viewpoint for the visual as well as labels and title.

10. Save Image

    To produce an animation a screenshot is taken of the html file by converting it to a 2D image.

11. Add Image to animation

    The image is stored to be "Stitched" to create the animation. In this way the final animation of the regions is not simulated or assumed in any way. Instead the animation simply provides and accumulated view over time. Due to the nature of the data a specific day or hour could be missing. To compensate for these pockets of incomplete data when an image is missing the prior view is extended.

Website

The ISSR data is published on the website http://catsr.ite.gmu.edu/Contrails.htm.

The following data is included:

- Week
- 3-D visualization GIF
- Max Volume during the week (%)
- Min Volume during the week (%)
- Avg. Volume during the week (%)
- Median Volume during the week (%)
- Abs Max Volume Rate of Change (%/4 hours)
- Abs Avg. Volume Rate of Change (%/4 hours)

- Max Ceiling (FL)
- Min Ceiling (FL)
- FL with Max Avg. Area during the week (FL)
- FL with Min Avg. Area during the week (FL)

Figure 6 includes a screenshot of the data on the page

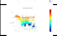
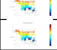
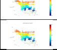
Date	3-D Viz	Max Volume (%)	Min Volume (%)	Average Volume (%)	Median Volume (%)	Max Ceiling (FL)	Min Floor (FL)	Abs Max Rate of Change (%/4 Hrs)	Abs Avg Rate of Change (%/4 Hrs)
Dec 31		12%	6%%	8%	9%	360	220	2	0.2
Jan 07		17%	5%	14%	14%	350	230	3	0.1
Jan 14		14%	6%	12%	12%	340	230	2	0.2
Jan 21		16%	4%	8%	11%	340	240	1	0.5

Figure 6: ISSR Data on the website

Conclusions

This paper describes the processing of publicly available NOAA data to generate 3-D visualizations of ISS region in the Contiguous US airspace.

The ISS regions will be used for flight planning in a future environment in which a "Contrail-cap" regulation is instituted. Airlines will earn credits for laying down persistent contrails in the morning and avoid laying contrails that persist in the evenings. Airlines can sell, swap or use credits for priority slot allocations in Traffic Management Initiatives (TMIs).

Additional research is underway to better understand the tradeoff between additional CO2 emissions resulting from additional along-track distance and flights at non-optimal cruise flight levels, and reductions in net radiative forcing. This tradeoff is complicated by the fact that CO2 emissions effect global warming in 20-40 years, while radiative forcing has an instantaneous effect.

Also additional analysis is required to address concerns on a concentration of flights on limited flight levels increasing traffic density.

The volume of data required for this type of analysis can grow rapidly. To keep the process manageable the weather data was restricted to every other data point. By dropping half the data points the visuals produced reflect geographic sections of 26 by 26 km. Despite this reduction the detail used in is sufficient for country wide visualizations.

Future Work

The ISSR location is the first step of an overall analysis capability that merges flight tracks/flight plans and Net Radiative Forcing models to evaluate the impact of flight plan choices on radiative forcing.

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