METHOD FOR ANALYSIS OF ICE SUPER SATURATED REGIONS (ISSR) IN THE U.S. AIRSPACE

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1 Abstract:

Contrails form when hot humid exhaust from jet engines mixes with a cold low pressure atmosphere creating long thin artificial clouds that are left behind by aircrafts. These high and thin cirrus clouds are highly transparent to shortwave radiation, and under certain azimuth angles, present a small Albedo Force allowing most of the incoming energy to reach the surface of the Earth. They do however absorb the outgoing longwave radiation, a portion of which is sent back to the Earth's surface, adding to the shortwave energy. The added energy causes the overall effect of the high thin cirrus clouds to enhance atmospheric greenhouse warming. Researchers estimate that contrails provide 7% of the Earth's cloud cover and may have a greater impact than CO_2 emissions. Adjusting flight trajectories could have an impact on greenhouse warming. Previous research mitigating the effects of contrails used only one month of data.

The paper describes the analysis of one year of high fidelity National Oceanic and Atmospheric Administration (NOAA) Rapid Refresh (RAP) data for the presence of Ice Super Saturated Regions (ISSRs). The highest frequency of ISSR was found during the months from June to September at Flight Levels between 300 and 350 where the maximum ISSR % Volume reached 30% of the US airspace. The ISSRs move constantly, however the largest regions identified were situated over the southern and eastern US air space.

1 Introduction

Condensation trails, or Contrails, are long, thin artificial clouds that can be created under certain conditions and left behind by aircrafts. Contrails were first noticed in the 1920's when the first high-altitude flights began. They became of importance during WWII when bombers could be sighted from miles away identified by their contrails. In 1953 H. Appleman established the conditions of relative humidity and temperature in which contrails will form [1]. In general, contrails form as hot humid exhaust from jet engines mixes with the cold low pressure atmosphere. The water vapor condenses and freezes on particles left by the engine's exhaust creating an artificial cloud.

Contrails are made of ice particles, as are cirrus clouds, and their shape and duration will depend on existing atmospheric conditions. These high and thin clouds are highly transparent to shortwave radiation, presenting a small albedo force, at certain sun azimuth angles, allowing most of the incoming energy to reach the surface. Although they do absorb a portion of the outgoing longwave radiation, a fraction is sent back to the surface adding to the shortwave energy [2]. The overall effect is therefore to enhance atmospheric greenhouse warming.

While modern climate science is still analyzing these scenarios, there is reason to believe contrails are a significant source of global greenhouse warming. In addition, in 1999 the IPCC estimated that contrails covered 0.1% of the Earth's surface and projected a grow to 0.5% by 2050, Additionally contrails may have a greater impact than CO_2 emissions. [3]

With forecast growth in air traffic there is potential for presence of contrails to increase. Kaiser [4] finds that in 2000 the global radiative forcing caused by persistent contrails was of 6.26 10^{-9} W/(m^2 hr contrail) compared to 3.785 10^{-11} W/(m^2 t_{CO2}) caused by CO_2. An optimized flight trajectory from Amsterdam Schiphol (EHAM) to Salzburg (LOWS) taking fuel burn and weather into account to minimize contrails, raised the fuel burn from 1.97 t to 2.00 t, but decreased the total RF [W m^{-2}] from 3.16 10^{-9} to 2.37 10^{-10} .

A study simulating the flight trajectory of 287 flights in U.S. airspace for the ISSR on one day

(4/10/2012) showed that the most energy efficient contrail reduction is achieved by changing the flight altitudes of aircrafts [5]. The simulation estimated a contrail formation time reduction from 5800 min to 2500 min. Gao showed that for a one day (4/12/2010) the adjustment of Flight Level to minimize contrails generates additional CO_2 from the additional fuel burn that outweighs the benefits of contrail avoidance [6]. In 2014, Grewe provides a simulation framework for climate-sensitive air traffic routing (REACT4C) [7]. To better assess the impact of ISSRs, their location, changes over a 24 hour period and over the course of a year is required.

This paper analyzes over 8500 weather files from the NOAA RAP (Rapid Refresh) assimilation/modeling system to identify ISSR. The files provide hourly snapshots of the weather over the CONUS airspace with a 3 km resolution. One year worth of files were collected, and the data was decoded and processed to identify areas presenting conditions needed to generate ISSR. For this analysis the conditions were specified as: Relative Humidity >= 100% and Temperature <= 233.15 K (-40°C). Relative Humidity was estimated by requiring that the Specific Humidity be >= 0.0001 kg/kg.

The analysis over the CONUS air space provided over one billion of three dimensional points where ISSR would have been present. The main results of the analysis are as follows:

- Seasons: ISSR can be found throughout the year with highest frequency during June, July, August and September. The monthly average % CONUS Volume is 20%, the minimum is 1% and the maximum is 38%.
- Altitudes: ISSR can cover over 10% of the airspace at Flight Levels from 320 to 370 with a peak of 30% of the airspace at Flight Level 340.
- Geographic Location: Results indicate that ice regions constantly vary in size and location, covering multiple states at a time. During peak months the largest regions were found on the eastern US air space.

This paper is organized as follows: Section 2 describes the conditions for contrail formation. Section 3 describes the method of analysis including the data sources and data processing. Section 4 describes the results. Section 5 provides a discussion and implications of these results.

2 Conditions required for contrail formation

Contrail formation will be thermodynamically expected at low temperatures, when there is an increase in relative humidity (RH) caused by the engine exhaust. Mixing the warm water vapor in a cool ambient air causes an increase in saturation. The water droplets form by condensation on soot and volatile particles left by the exhaust, and freeze forming ice particles. The trail of ice particles left behind the engines creates a “man-made” cirrus cloud.

Typically, contrails form at altitudes, above 8 km (26,000 ft) and temperatures below -40°C. The temperature to altitude ratio in Figure 1 provides this relation along with the RH requirements [8].

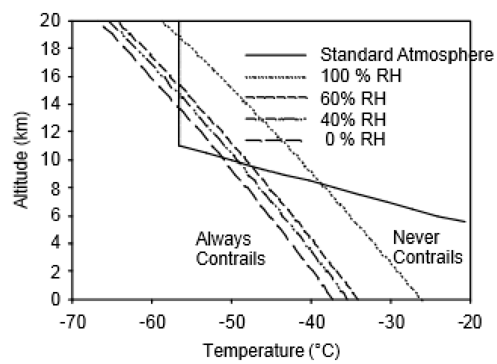


Figure 1 Temperature vs Altitude required for control formation (Schumann, 2005)

The diagram in Figure 1 includes Relative Humidity, which is generally expressed as a percentage and represents the actual amount of water vapor in the air compared to the total amount of vapor that can exist in the air at its current temperature. Warm air can hold more water vapor than cold air, therefore an equal amount of water will yield a higher relative humidity in cooler air.

The intent of this analysis is not to focus on any specific aircraft or engine; but on the overall conditions under which contrails form, therefore we focus only on atmospheric conditions Temperature and RH.

3 Method of Analysis

This section describes the source of data and the algorithm for processing the data.

3.1 Weather Data Source

Weather data used is provided in a GRIB (General Regularly-distributed Information in Binary form) file available to the public by the National Oceanic and Atmospheric Administration (NOAA) through its National Climatic Data Center (NCDC). For this analysis we used Rapid Refresh Products (RAP), Regional – CONUS, 130. The files provide weather indicators under a Lambert Conformal projection with a 13-km resolution. The data contains a grid of weather points with dimensions (Nx = 451, Ny = 337) forming each plane and Z vertical levels. Going forward each location in Nx, Ny, Z is referred to as a 3D point.

The NOAA provides RAP files with both actual and forecasted data. This analysis uses the actual RAP files provided at the top of each hour. For this analysis we extracted one year of data which will include 24 files per day, or 8760 files in the year.

3.2 Conditions to form ISSR in terms of GRIB file.

For the purpose of identifying regions where contrails can form, we require a temperature at or below –40°C (233.15 K) and a Relative Humidity of 100%. The temperature in Kelvin is provided within the file, and these records can be directly identified; however the relative humidity is not explicitly provided. The file does provide a measurement of the specific humidity. To estimate the relative humidity we can leverage vapor saturation tables. From the table, we take that at –40°C, 0.1 g/kg (or 0.0001 kg/kg) of water vapor is sufficient to saturate the air. Any additional humidity, such as that provided by the engine's exhaust will result in condensation generating contrails.

3.3 Data Preprocessing

To process one year worth of data, the algorithm must sweep through 8,500 files, decode the GRIB format and then extract values. Each GRIB file is over 30 MB of text.

Step 1 is to sweep through these files, preprocess them, and load the data to a database. In an effort to reduce the amount of data to be processed and loaded, the first time the GRIB files are read, only 3D points that meet the ISSR criteria are extracted and each location is recorded along with its significant data in a table format to be loaded to the database. This analysis included temperature, pressure, specific humidity, and flight level.

Step 2 The data is summarized aggregating the 3D points by day, month and Flight Level to obtain basic statistics of the regions frequency and elevation. This information can then be used to identify ISSR seasonality and elevation.

Step 3 With the dates of interests identified the data is reprocessed plotting 3D points that met ISSR criteria over a US map. The resulting image provides a view of the geographic location of the ISSR.

3.4 Metrics

The objective of the analysis of the ISSR regions is to measure the frequency of occurrence and coverage (latitude/longitude and altitude).

Horizontal Coverage Estimation

To estimate the coverage of the ISSR at each Flight Level the quantity of identified Ice Saturated 3D points is compared to the total coordinates in the grid:

$$\%\, CONUS\ Volume = \frac{Count\ of\ ISSR}{Coordinates\ in\ Grid}$$

Where:

$$\boldsymbol{Count\ of\ ISSR} = \text{3D points that satisfy the requirements within the month and Flight Level}$$

$$\boldsymbol{Coordinates\ in\ Grid} = (Nx)(Ny)\ (Days\ in\ month)(24\ hr) = (151{,}987)\ (Daysmonth\ )(24)$$

4 Results

Eight thousand five hundred (8,500) weather files with over 1.1 billion 3D points were processed for the 10 month period from November-2014 to September-2015. January 2015 and October 2015 data were incomplete at the time of extraction and were excluded from the analysis. Two hundred gigabytes of data storage memory were required (200 GB).

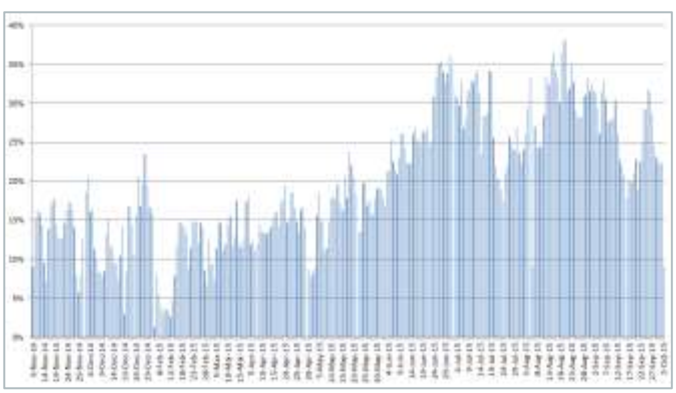
Table 1 provides a summary of the 3-D points that satisfied the ISSR criteria in each month of the year. The counts are accumulated over all locations in the CONUS and between FL260 and FL430.

Month	ISSR 3D Points
Nov-14	74,824,885
Dec-14	119,620,620
Feb-15	75,914,792
Mar-15	53,062,235
Apr-15	117,785,246
May-15	125,198,897
Jun-15	141,546,155
Jul-15	157,982,212
Aug-15	159,774,348
Sep-15	144,327,376
Total	1,170,036,766

Table 1 Count of 3D points by Month

4.1 Seasonality

The % CONUS Volume of the airspace at FL 430 for each day of the year is shown in Figure 3.



The annual average % Volume is 18%, the minimum is 6% and the maximum is 30%.

The daily average percentage of CONUS Volume at Flight Level 340 is shown in Figure 2. ISSR % CONUS Volume is highest during the summer months (June to September) with a peak of 30% coverage during August. The monthly average % Volume is 20%, the minimum is 1% and the maximum is 38%.

Figure 2: Daily ISSR % CONUS Volume

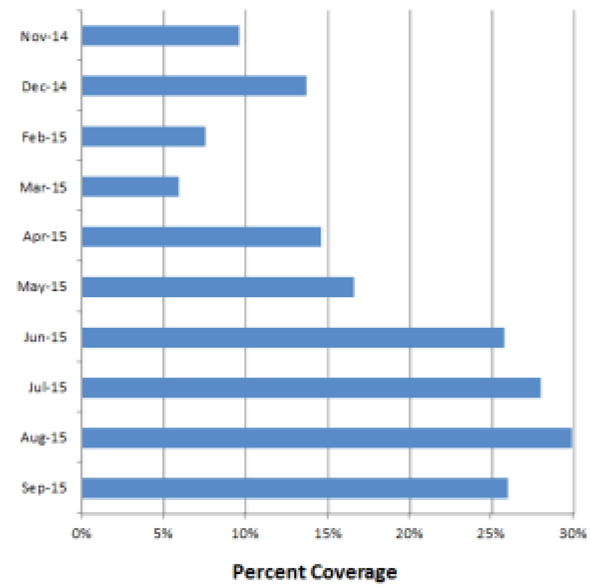


Figure 3 Average Montly ISSR % CONUS Volume

Figure 4 provides an overall view of the seasonality by Flight Level. Seasonality can be seen with a high season from June to September, however ISSR are present thought the year. All seasons show a higher volume between Flight Levels 320 and 340.

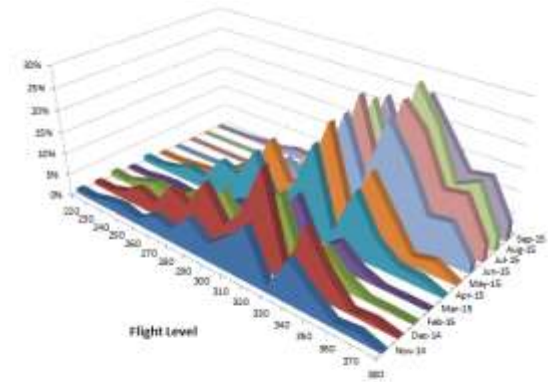


Figure 2 Percentage of ISSR Coverage in the US Airspace 2015

4.2 Vertical frequency

The coverage of the CONUS at each altitude during the month of August 2015 is shown in Figure 5. ISSRs are present from Flight Levels 280 to 380. The most frequent occurrence is at Flight Level 340.

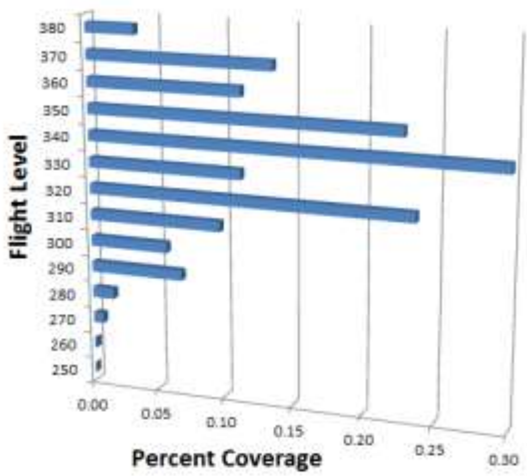


Figure 3 Average ISSR coverage by Flight Level in August 2015 (%)

The effect of seasonality by Flight Level is shown in Table 2. During February and March 2015 no ISSR were identified above Flight Level 350.

Table 2 ISSR frequency by Flight Level (Percentage of total air space)

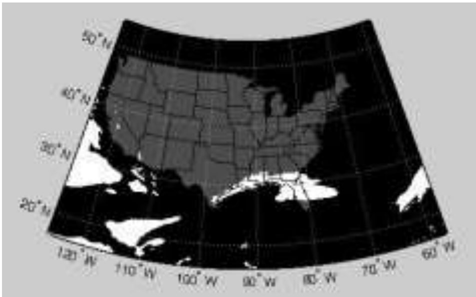
Flight Level	Nov-14	Dec-14	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15
380	0	0	0	0	0	0	2	4	4	4
370	2	1	0	0	2	3	9	13	14	13
360	1	1	0	0	2	2	9	12	11	12
350	5	6	3	2	6	9	18	23	23	19
340	10	14	8	6	15	17	26	28	30	26
330	2	3	2	2	4	7	11	11	11	11
320	12	22	15	12	21	24	24	26	24	23
310	8	11	9	5	10	10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

Figure 6 combines the max and min Flight Levels in blue and red, along with the average ISSR coverage in green.

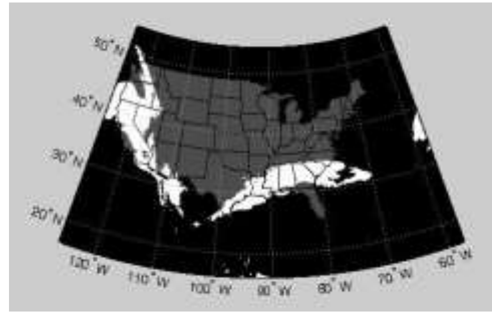
Figure 6 Average ISSR coverage by Flight Level in August 2015 (%)

4.3 Geographic location

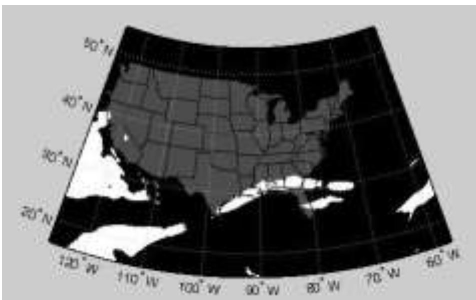
Figures 7 and 8 provide a view of the geographic location of the ISSRs and their changes while varying the month, day and altitude of the sample. Snapshots were taken from November 15th 2014 and August 18th 2015 and provide a clear view of the seasonality. The effect of altitude is most present when comparing charts during August. Last, the snapshots are provided in hour by hour increments to provide a view of the speed at which these regions move.



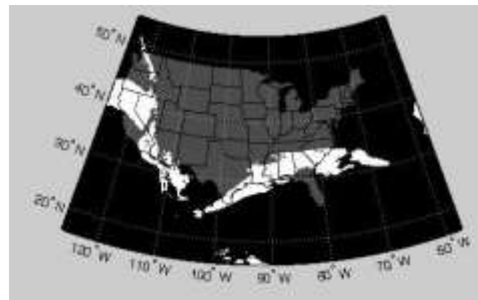
November 15th 2014 t:08:00 FL 340



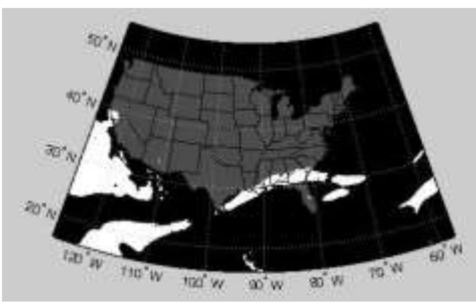
November 15th 2014 t:08:00 Z:26 FL 360



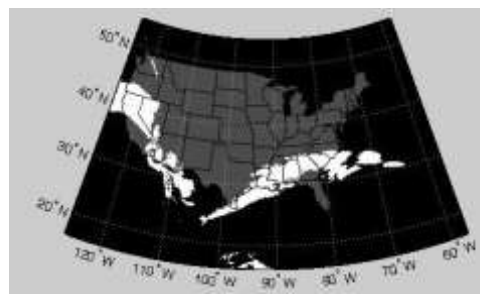
November 15th 2014 t:09:00 FL 340



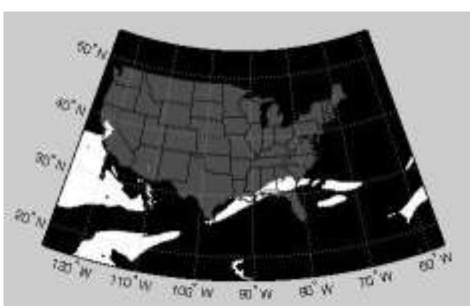
November 15th 2014 t:09:00 FL 360



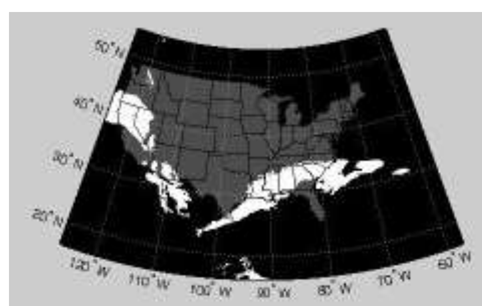
November 15th 2014 t:10:00 FL 340



November 15th 2014 t:10:00 FL 360

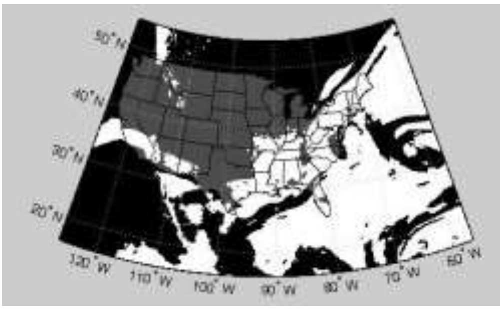


November 15th 2014 t:11:00 FL 340

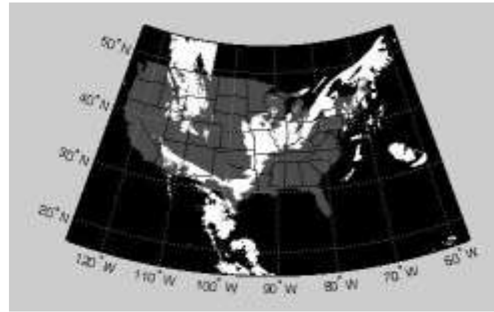


November 15th 2014 t:11:00 FL 360

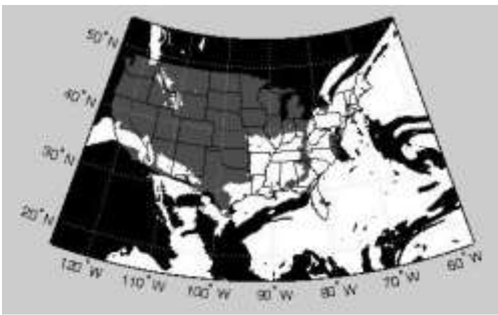
Figure 7 ISSR coverage November 2014 (%)



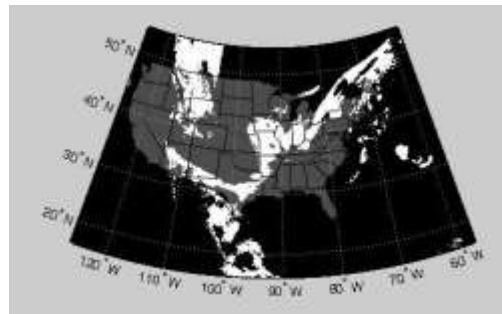
August 18th 2015 t:09:00 FL 340



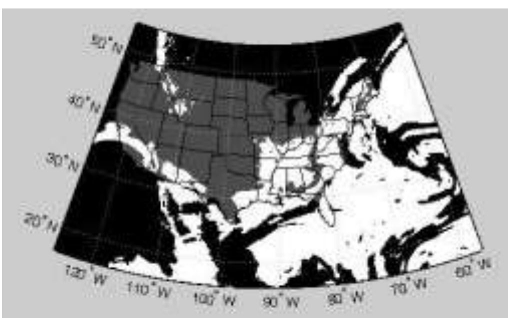
August 18th 2015 t:09:00 FL 360



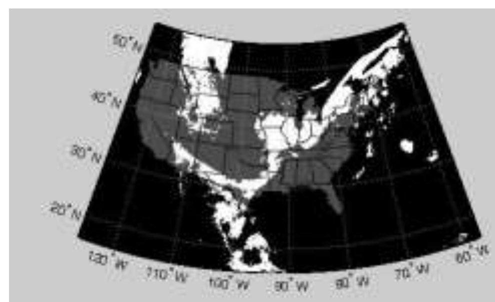
August 18th 2015 t:10:00 FL 340



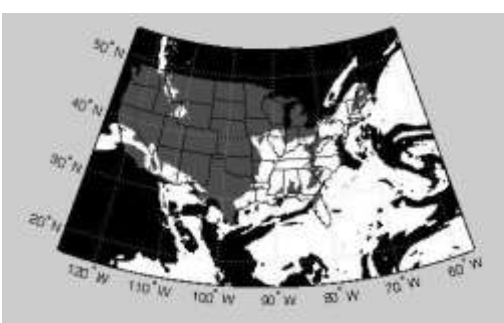
August 18th 2015 t:10:00 FL 360



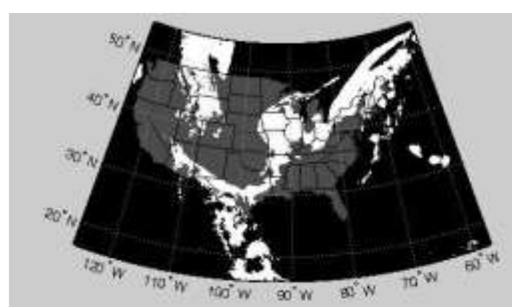
August 18th 2015 t:11:00 FL 340



August 18th 2015 t:11:00 FL 360



August 18th 2015 t:12:00 FL 340



August 18th 2015 t:12:00 FL 360

Figure 8 ISSR coverage August 2015 (%)

5 Conclusion

In its original GRIB format the RAP weather data requires a programmed algorithm to read and decode the information. The method presented provides a means to consolidate the information from the 8,500 weather files and analyze the data. A first exploration of the data identified seasonality, altitude and geographic location of ISSRs. This analysis presented an overall view of the ISSRs but more a detailed breakdown can be performed on a specific Flight Level, date range, location or a combination of factors.

The examination of the data shows how the ISSRs vary significantly by altitude and location. These results attest to the fact that any attempt to use weather data to prevent contrails requires current weather information and an exact flight path. However, once these are obtained the method presented can be used to perform regular updates of weather data and the variability in ISSRs could be exploited for flight path planning.

5.1 Summary of Results

- Seasons: ISSR can be found throughout the year with highest frequency during June, July, August and September. The monthly average % CONUS Volume is 20%, the minimum is 1% and the maximum is 38%.
- Altitudes: ISSR can cover over 10% of the airspace at Flight Levels from 320 to 370 with a peak of 30% of the airspace at Flight Level 340.
- Geographic Location: Results indicate that ice regions constantly vary in size and location, covering multiple states at a time. During peak months the largest regions were found on the eastern US air space.

5.2 Future Work

5.2.1 Improvements in Weather Data Analysis

At the time this data was collected January 2015 and October 2015 data were incomplete and were excluded from the analysis. Completion of these months and regular updates to include an addition year of weather information can provide a trend and improve these results.

Statistical analysis of the data could provide additional insight the weather information.

5.2.2 Use of forecasted Weather Data

Matching historic and current weather data to flight information provides insight to the possibility of contrail formation; however, once the weather surrounding the flight path can accurately be determined the current weather files could be extended with forecasted weather data corresponding to the time of flight for more accurate prediction.

5.2.3 Exploiting Azimuth Angle

Once contrail generation can be forecasted with geographic location and time of day; an additional analysis could consider the azimuth. This will enable examining the effect produced by the angle at which the sun penetrates the contrails to better predict the climate impact it might have.

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