Contrail Reduction Strategies Using Different Weather Resources

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Two weather products used extensively in aviation are the wind, temperature and humidity forecast as part of the Rapid Update Cycle and the weather forecast provided by the Corridor Integrated Weather System. These weather forecasts have been used to estimate traffic delays and to design aircraft routes avoiding severe weather. The Rapid Update Cycle forecast has been used to strategically plan reductions of aircraft induced contrails. Currently, concepts for weather avoidance and contrail reduction are separate. This paper uses these two weather forecasts in a complementary way to develop contrail reduction strategies in the presence of different weather conditions. The concept of contrail frequency index is used to quantify the severity of contrail formation and is modified with additional weather information. The contrail frequency index is defined as the number of aircraft flying through regions that would form contrails during a period of time. When the weather forecast indicates that there were already clouds in the regions, the index is discounted. The index is used to identify the air traffic control centers and altitudes with high potential for contrail formation in the next few hours. This is so that different strategies can be used to reduce the contrail formation in the entire airspace by altering the aircraft cruising altitudes. When severe weather is present, the feasibility of the strategies will be evaluated. For the day tested, contrail frequency index was discounted by 14% when taking into account the effect of cloud coverage. The contrail reduction strategy achieves a 63.7% contrail reduction taking into account the weather impact if the aircraft are allowed to alter their cruising altitude by 2,000 feet, and a 92.6% reduction if by 4,000 feet. The proposed contrail reduction strategies are suitable for reducing contrail formation in the entire airspace with the presence of different weather conditions.

I. Introduction

Interest in the effect of aircraft condensation trails or contrails on climate change has increased in recent years.[1] Contrails form in the wake of aircraft for various reasons but the most important is the emission of water vapor.[2] They appear and persist if the aircraft location has certain atmospheric conditions. The global mean contrail cover in 1992 is estimated to double by 2015, and quadruple by 2050 due to the increase in air traffic.[3] Studies suggest that the environmental impact from persistent contrails may be three to four times,[4] or even ten times[5] larger than that from aviation induced emissions. Therefore, methods of persistent contrail reduction need to be explored to reduce aircraft induced environmental impact.

Efforts have been made in the past years to design strategies for reducing persistent contrail formations. Gierens[6] and Noppel[7] reviewed various strategies for contrail avoidance including changing engine architecture, enhancing airframe and engine integration, using alternate fuels, and modifying traffic flow management procedures. Among the traffic flow management solutions, Mannstein[8] proposed a strategy to reduce the climate impact of contrails significantly by small changes to each aircraft's flight altitude. Campbell[9] presented a mixed integer programming methodology to optimally reroute aircraft to avoid the formation of

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persistent contrails. Fichter[10] showed that the global annual mean contrail coverage could be reduced by reducing the cruise altitude. Williams[11,12] proposed strategies for contrail reduction by identifying fixed and varying maximum altitude restrictions. Sridhar proposed strategies that minimize the persistent contrail formation by altering aircraft cruising altitudes in a fuel efficient way[13] and proposed methods of contrails avoidance in the presence of winds.[14] These methods did not take into account the effect of existing cloud coverage and the presence of severe weather.

The objective of this paper is to develop contrail reduction strategies using diverse weather resources. Two weather products were used in this paper, the wind, temperature and humidity forecast provided in the National Oceanic and Atmospheric Administration's Rapid Update Cycle and the weather forecast provided by the FAA's Corridor Integrated Weather System. Currently, concepts for the weather avoidance strategy and contrails reduction strategy are done exclusively.[13–16] This paper uses the two weather products in a complementary way to develop contrail reduction strategies in the presence of different weather conditions. The concept of contrail frequency index was used to quantify the severity of contrail formation.[17] The contrail frequency index was defined as the number of aircraft flying through regions that would form contrails during a period of time. When the weather resource indicated that there were already clouds formed in the regions, the index was discounted. The indices are used to identify the air traffic control centers and altitudes with high potential contrail formation in the next few hours such that different strategies can be used to alter the aircraft cruising altitudes to reduce the contrail formation in the entire airspace. When severe weather presents, the feasibility of the strategies will be evaluated using the weather information. The proposed contrail reduction strategies are suitable for reducing the contrail formation in the entire airspace with the presence of clouds and severe weather conditions.

The remainder of the paper is organized as follows. Section II provides the descriptions of weather and contrail weather models. Section III demonstrates the correlations between contrail and cloud coverage regions. Section IV derives the contrail frequency index using different weather resources and its usage for contrail reduction strategies. Finally, a summary and conclusions are presented in Section V.

II. Models

A. Weather Model

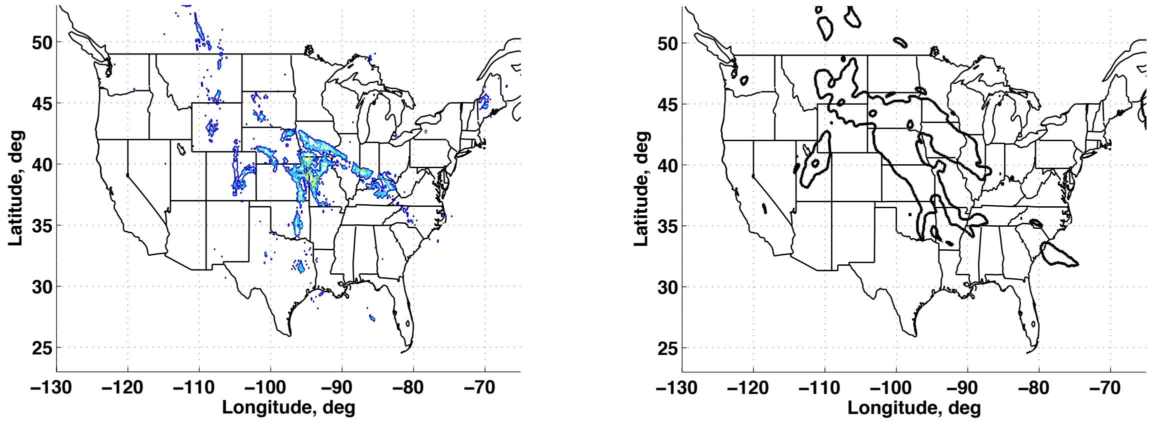
This paper uses the FAA's Corridor Integrated Weather System (CIWS) weather model.[18] CIWS provides accurate, low-latency, high-resolution three-dimensional (3D) weather information and forecasts for up to two hours. It has a temporal resolution of two and a half minutes and a spatial resolution of one kilometer by one kilometer. The CIWS 3D weather depiction is composed of two main product types: precipitation, or vertically integrated liquid (VIL), and echo tops. Figure 1a shows the CIWS precipitation information at 8AM eastern daylight time (EDT) on April 23, 2010. The colors indicate the VIL level, where blue is VIL level 1 and 2, light blue is 3, yellow is 4, and red is 5 and 6. VIL level 1 and above indicate the presence of precipitations and were used to identify the clouds coverage regions. In addition, pilots would generally penetrate VIL level less than 3 and avoid regions with VIL level 3 and above.[19]

CIWS also provides echo tops information, which indicate the storm heights. Echo tops were used to provide three dimensional weather information. It is assumed that the storm is having impacts from ground level up to the height of the storm tops.

B. Contrail Model

Contrails are vapor trails caused by aircraft operating at high altitudes under certain atmospheric conditions. The contrail model in this paper uses atmospheric temperature and humidity data retrieved from the Rapid Updated Cycle (RUC) data, provided by the National Oceanic and Atmospheric Administration (NOAA). The horizontal resolution in RUC is 13-km. RUC data has 37 vertical isobaric pressure levels ranging between 100 and 1000 millibar (mb) in 25 mb increments. Since the vertical isobaric pressure levels do not correspond with 2,000 feet increments, linear interpolation was used to convert the RUC data to a vertical range from 26,000 feet to 44,000 feet with an increment of 2,000 feet. The range is chosen because it generally is too warm to form contrails below 26,000 feet and most aircraft fly below 44,000 feet.

Contrails form when a mixture of warm engine exhaust gases and cold ambient air reaches saturation with respect to water, forming liquid drops which quickly freeze. Contrails form in the regions of airspace that have ambient Relative Humidity with respect to Water (RHw) greater than a critical value r_{contr}.[20] Regions



(a) CIWS Precipitation

(b) Contrail Favorable Regions

Figure 1. CIWS weather and contrail regions at 8AM EDT on April 23, 2010.

with RHw greater than or equal to 100% are excluded because clouds are already formed.[21] Contrails can persist when the environmental Relative Humidity with respect to Ice (RHi) is greater than 100%.[22] In this paper, contrail favorable regions are defined as the regions of airspace that have $r_{contr} \leq RHw < 100\%$ and $RHi \geq 100\%$.

The estimated critical relative humidity for contrails formation at a given temperature T (in Celsius) can be calculated as

$$r_{contr} = \frac{G(T - T_{contr}) + e^{liq}_{sat}(T_{contr})}{e^{liq}_{sat}(T)}, \quad (1)$$

where $e^{liq}_{sat}(T)$ is the saturation vapor pressure over water at a given temperature. The estimated threshold temperature for contrails formation at liquid saturation is

$$T_{contr} = -46.46 + 9.43\ln(G - 0.053) + 0.72\ln^2(G - 0.053), \quad (2)$$

where

$$G = \frac{EI_{H_2O} C_p P}{\epsilon Q(1 - \eta)}, \quad (3)$$

EI_{H_2O} is the emission index of water vapor (assumed to be 1.25); $C_p = 1004$ (in $JKg^{-1}K^{-1}$) is the isobaric heat capacity of air, P (in Pa) is the ambient air pressure, $\epsilon = 0.6222$ is the ratio of molecular masses of water and dry air, $Q = 43 \times 10^6$ (in JKg^{-1}) is the specific combustion heat, and $\eta = 0.3$ is the average propulsion efficiency of the jet engine. The value of r_{contr} is computed by Eq (1)-(3) using RUC measurements for RHw and temperatures. RHi is calculated by temperature and relative humidity using the following formula:

$$RHi = RHw \times \frac{6.0612e^{18.102T/(249.52+T)}}{6.1162e^{22.577T/(237.78+T)}}, \quad (4)$$

where T is the temperature in Celsius. Figure 1b shows the contrail favorable regions at 8AM EDT on April 23, 2010 at an altitude of 34,000 feet.

III. Analysis

Contrail favorable regions can be computed and predicted using the weather forecasts. One might ask what if there are already clouds in regions favorable for contrail formation. In that case, it does not matter if contrails are formed or not since the incoming and outgoing radiations are reduced anyway. That is, aircraft should be able to fly through these regions without causing negative environmental impact. On the other hand, if the weather condition is too severe to safely fly through, aircraft should avoid the regions even though doing so would reduce the contrail formations. In order to take into account these effects, precipitation prediction is used to modify the contrail models.

To observe the correlations between contrail favorable and precipitation (VIL level 1 and above) regions, the two regions in Fig. 1 were overlapped and shown in Fig. 2. In the figure, the green polygons indicates the regions of CIWS precipitation and the grey contours are the contrail favorable regions over twenty U.S. air traffic control centers. As shown in the figure, the locations of contrail favorable and CIWS precipitation are correlated. In fact, there are 48% of CIWS precipitation regions overlapped with contrail favorable regions. Therefore, the effect should not be ignored.

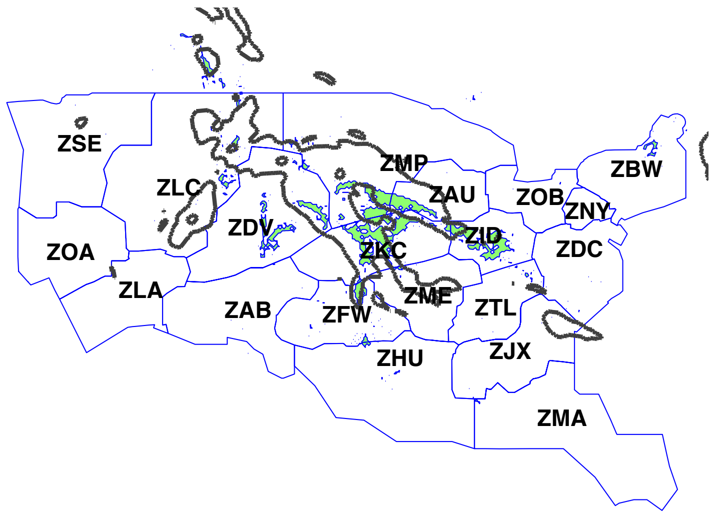


Figure 2. Contrail favorable and CIWS precipitation regions overlapped at 8AM EDT on April 23, 2010.

Figure 3 shows the correlations between CIWS precipitation and contrail favorable regions in April 2010. The blue line indicates the size of the CIWS precipitation, defined as the number of grid points in 13km RUC 451 × 337 grid with CIWS VIL level 1 and above. The green line is the number of grid points that are overlapped with contrail favorable regions. During the month, there are 53% of CIWS VIL level 1 and above overlapped with contrail favorable regions. The yearly data of 2010 have the similar trend.

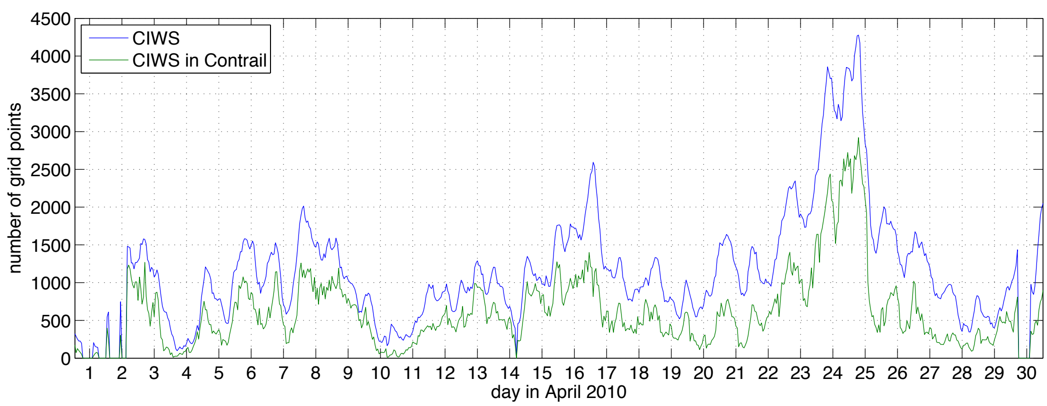


Figure 3. CIWS precipitation regions overlapped with contrail favorable regions in April 2010.

The average ratios of CIWS precipitation overlapped with contrail favorable regions at different altitudes over the year of 2010 are shown in Fig. 4. The coverage ratios vary with altitudes. The maximum coverage ratio at each month ranges from 19.0% (November, 34,000 feet) to 45% (January, 34,000 feet). It is noted that in summer the coverage ratios are larger at higher altitude (July and August at 40,000 feet), while the ratios are higher at lower altitude in winter (January and December at 34,000 feet). The observation can be interpreted as contrail favorable regions are larger at higher altitude in summer because of the warm temperature at lower altitude. In July and August, there are no contrail favorable regions formed at 26,000 and 28,000 feet.

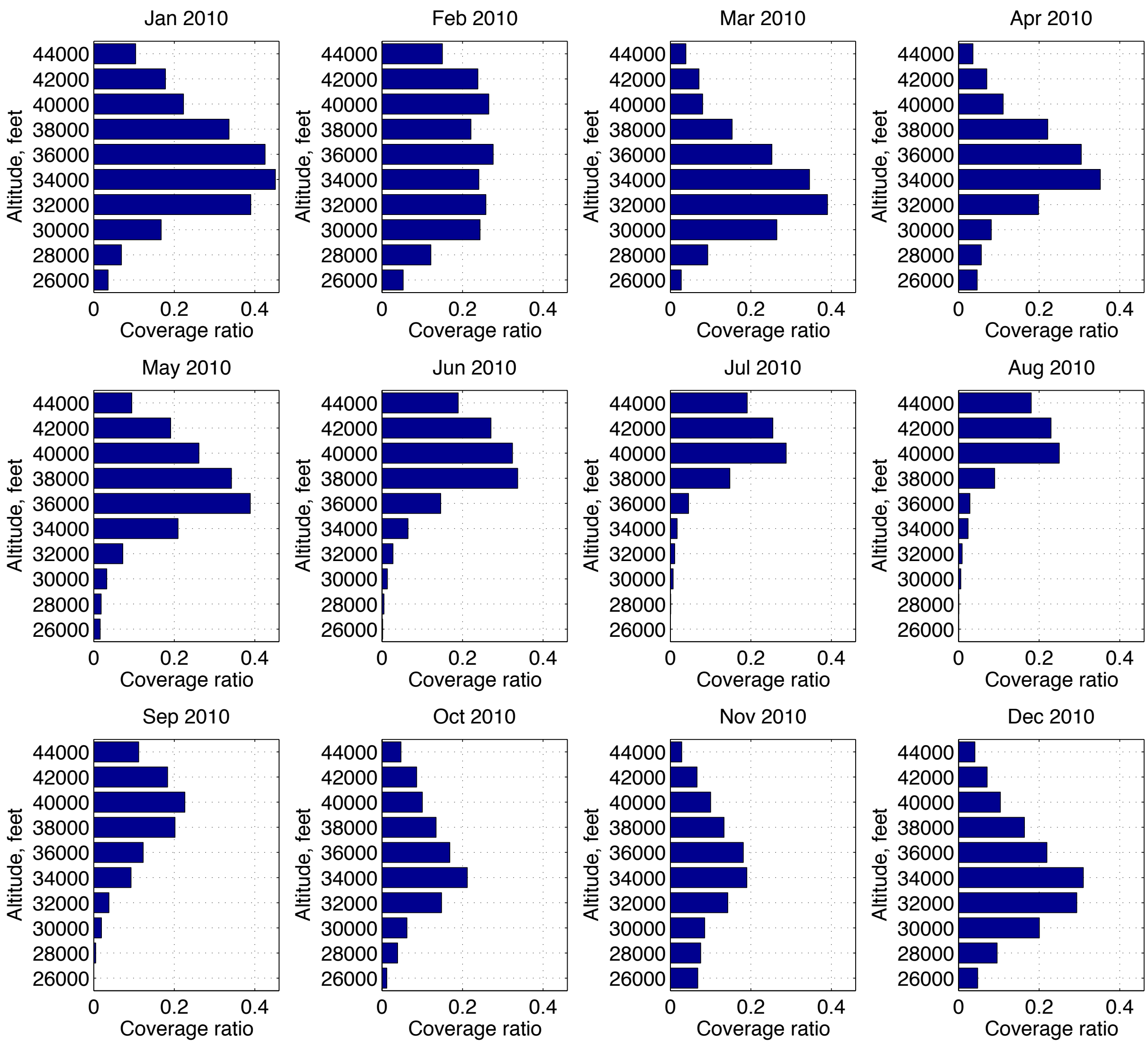


Figure 4. Overlap ratio between CIWS precipitation and contrail favorable regions in 2010.

Since there are overlapped regions between the two that can not be ignored, the development of contrail formation analysis and reduction strategies should take into account the effect of precipitation. Another observation is that the contrail reduction strategies should be more efficient in winter than in summer since the contrail favorable regions in summer happen more frequently at high altitude (40,000 feet and above) where fewer aircraft are flying. The contrail formation analysis and reduction strategies in the presence of different weather conditions are described in the next section.

IV. Methodologies

A. Contrail Frequency Index

This paper modifies the contrail frequency index (CFI) defined in Ref. 17 by adding the component of cloud coverage information and using 13km RUC data instead of 40km RUC data. The altitude level index, l, is defined as $l = 1 \ldots 10$ corresponding to altitudes of $26,000, 30,000, \ldots, 44,000$ feet. The potential persistent contrail formation matrix (contrail matrix) at time t at level l is defined as

$$\mathbf{R}_t^l = \begin{bmatrix} r_{1,1,t}^l & r_{1,2,t}^l & \cdots & r_{1,451,t}^l \\ \vdots & \vdots & \ddots & \vdots \\ r_{337,1,t}^l & r_{337,2,t}^l & \cdots & r_{337,451,t}^l \end{bmatrix}, \tag{5}$$

where $r_{i,j,t}^l$ is 1 if $r_{contr} \leq RHw < 100\%$ and $RHi \geq 100\%$ at grid (i,j), and 0 if not. The Center contrail frequency indices of twenty U.S. air traffic control centers at time t at level l are defined as

$$CFI_{center,l,t} = \sum_{i=1}^{337} \sum_{j=1}^{451} r_{i,j,t}^l a_{i,j,t}^l c_{i,j}, \tag{6}$$

where $a_{i,j,t}^l$ is the number of aircraft within RUC 13km grid (i,j) flying closest to altitude level l at time t, and $c_{i,j}$ is 1 when grid (i,j) is inside the center and 0 if not. The twenty U.S. air traffic control centers are listed in Table 1. Contrail frequency index is used to quantify the severity of contrail activities.

Table 1. Center index of twenty continental U.S. air traffic control centers.

Index	Name	Index	Name
1	Seattle Center (ZSE)	11	Chicago Center (ZAU)
2	Oakland Center (ZOA)	12	Indianapolis Center (ZID)
3	Los Angeles Center (ZLA)	13	Memphis Center (ZME)
4	Salt Lake City Center (ZLC)	14	Cleveland Center (ZOB)
5	Denver Center (ZDV)	15	Washington D. C. Center (ZDC)
6	Albuquerque Center (ZAB)	16	Atlanta Center (ZTL)
7	Minneapolis Center (ZMP)	17	Jacksonville Center (ZJX)
8	Kansas City Center (ZKC)	18	Miami Center (ZMA)
9	Dallas/Fort Worth Center (ZFW)	19	Boston Center (ZBW)
10	Houston Center (ZHU)	20	New York Center (ZNY)

For planning for contrail reduction stretegies, traffic flow managers need to know the potential high contrail regions in the next few hours. Therefore predicted contrail frequency index is needed for contrail reduction strategies. Similar to the concept of Weather Impacted Traffic Index (WITI) introduced by Callaham et al.[23] and Sridhar,[24] and the three-dimensional index derived by Chen,[15] predicted contrail frequency index was defined as a convolution of predicted traffic data and forecast of atmospheric conditions. The index consists of the RUC forecast data and the predicted aircraft locations when t is a future time. The Center contrail frequency index can then be rewritten as

$$CFI_{center,l,t} = \begin{cases} \sum_{i=1}^{337} \sum_{j=1}^{451} r_{i,j,t}^l a_{i,j,t}^l c_{i,j} & \text{if } t <= t_{now}, \\ \sum_{i=1}^{337} \sum_{j=1}^{451} \hat{r}_{i,j,t}^l \hat{a}_{i,j,t}^l c_{i,j} & \text{if } t > t_{now}, \end{cases} \tag{7}$$

where t_{now} is the current time, $\hat{r}_{i,j}^l$ is defined in Eq. (5) with RUC forecast data, and $\hat{a}_{i,j}^l$ is the predicted number of aircraft within RUC 13km grid (i,j) flying closest to altitude level l at time t. Based on the assumption that there are already clouds in regions with VIL level 1 and above, CFI should be discounted when the contrail favorable and CIWS VIL level 1 and above regions overlapped. However, regions with VIL level 3 and above are consider severe storms and pilots would try to avoid those regions. Contrail favorable regions are considered as soft constraint areas, meaning it is fine to fly through, but better to avoid for reducing the environmental impact. Severe weather regions are considered as hard constraint areas that pilots would try to avoid. In order to incorporate these constraints in the contrail reduction strategies, the

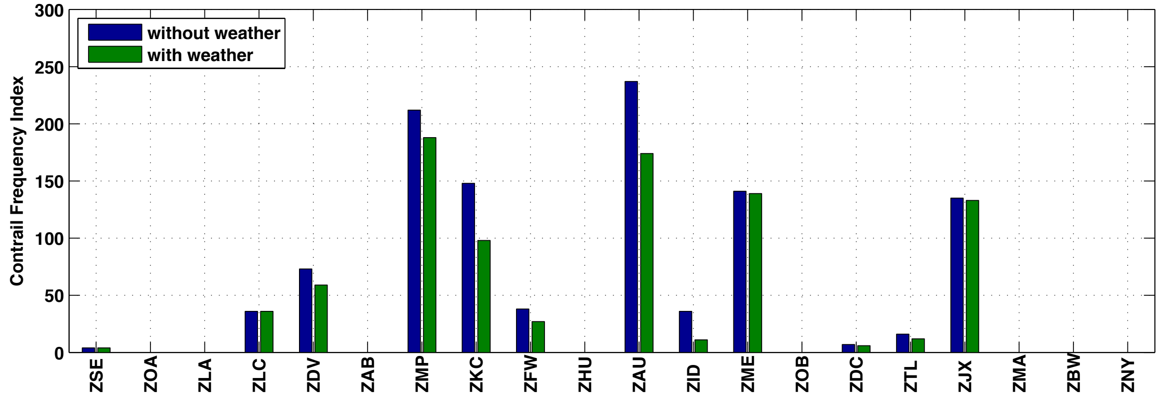


Figure 5. Contrail frequency index with and without weather information at 34,000 feet at 8AM EDT on April 23, 2010.

VIL level matrix that maps the CIWS data to 13km RUC grid is defined as

$$\mathbf{W}_t^l = \begin{bmatrix} w_{1,1,t}^l & w_{1,2,t}^l & \cdots & w_{1,451,t}^l \\ \vdots & \vdots & \ddots & \vdots \\ w_{337,1,t}^l & w_{337,2,t}^l & \cdots & w_{337,451,t}^l \end{bmatrix}, \tag{8}$$

where $w_{i,j,t}^l$ is the CIWS VIL level if the echo top at grid (i, j) is higher than altitude level l at time t. $w_{i,j,t}^l$ is zero if the echo top at grid (i, j) is lower than altitude lvl l. The $r_{i,j,t},^l$ in Eq (5) will be set to zero if $w_{i,j,t}^l$ is 1 or 2. This matrix will later be used to evaluate the feasibility of the contrail reduction strategies.

As an example, the Center contrail frequency indices with and without weather information at 34,000 feet at 8AM EDT on April 23, 2010 were computed and are shown in Fig. 5. The blue bars are the CFI without weather information. When the contrail favorable regions are covered by CIWS VIL level 1 or 2, the CFI was discounted, as represented by the green bars. For ZMP, ZKC, and ZAU centers, the CFIs without weather information are 212, 148 and 237 respectively, while the CFIs without weather information are 188, 98 and 174 respectively. The CFI differences in these centers are more significant as there are more regions with VIL 1 and 2 overlapped with contrail favorable regions (see Fig. 2).

Figure 6 shows the aircraft trajectories and contrail formations in Kansas City Center. In the figures, the grey polygon indicates the contrail favorable regions. Blue dots are the flying aircraft between 33,001 feet and 35000 feet. When the aircraft enter the grey polygon, contrails would form, as indicated by grey dot. The number of grey dots in Fig. 6a are the CFI without weather information, which is 148. The green polygon in Fig. 6b are the regions with CIWS VIL level 1 and 2. When an aircraft flies through a grey polygon (contrail favorable regions) overlapped with a green polygon, the aircraft is already covered by clouds therefore it should not be counted toward CFI. There are total of 50 grey dots that are inside green polygons, bringing down the CFI with weather information to 98.

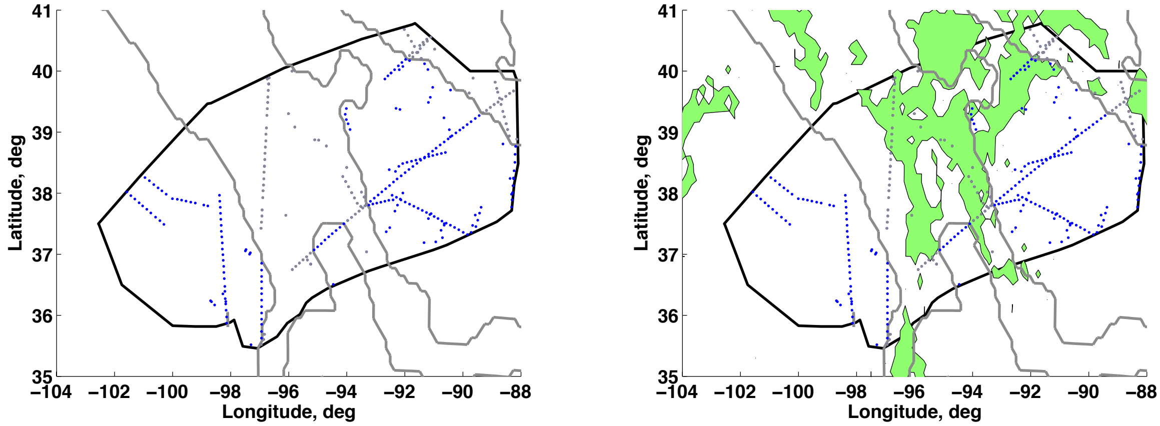
In order to determine if it is feasible to perform the contrail reduction strategies, the Weather Severity Index (WSI) is defined as the number of aircraft that would be impacted by the severe weather in a future time, formulated as

$$WSI_{center,l,t} = \sum_{i=1}^{337} \sum_{j=1}^{451} \hat{w}_{i,j,t}^l \hat{a}_{i,j,t}^l, \tag{9}$$

where $\hat{w}_{i,j}^l$ is defined in Eq. (8) with CIWS forecast data, and $\hat{a}_{i,j}^l$ predicted number of aircraft within RUC 13km grid (i, j) flying closest to altitude level l at time t. Note that the WSI is the same concept with WITI in Ref. 24 and is used to determine the feasibility of applying the proposed contrail reduction strategies.

B. Contrail Reduction Strategies

This paper extends the contrail reduction strategies developed in Ref. 13 by adding the component of cloud coverage information. Two changes are made. One is to discount the CFI when the CIWS VIL level is 1



(a) without CIWS precipitation

(b) with CIWS precipitation

Figure 6. CIWS precipitation and contrail regions at 8AM EDT on April 23, 2010.

and 2, as described in the previous subsection. Second is to use the weather severity index as an indicator to decide whether the strategy is feasible or not.

Contrail frequency indices are used to quantify the severity of contrail formation. The strategy for reducing the persistent contrail formations is to minimize contrail frequency index by altering the aircraft's cruising altitude. Assume the aircraft at altitude level l at a center are made to fly a different level l'. The contrail frequency index changes to

$$CFI^{l'}_{center,l,t} = \sum_{i=1}^{337}\sum_{j=1}^{451} r^{l'}_{i,j,t} a^{l}_{i,j,t} c_{i,j}, \tag{10}$$

A contrail frequency index matrix is formed as

$$\mathbf{CFI}_{center,t} = \begin{bmatrix} CFI^1_{1,t} & CFI^1_{2,t} & \dots & CFI^1_{11,t} \\ CFI^2_{1,t} & CFI^2_{2,t} & \dots & CFI^2_{11,t} \\ \vdots & \vdots & \ddots & \vdots \\ CFI^{11}_{1,t} & CFI^{11}_{2,t} & \dots & CFI^{11}_{11,t} \end{bmatrix}, \tag{11}$$

where the diagonal term $CFI^l_{l,t}$ is the contrail frequency index at level l before contrail reduction, and $CFI^{l'}_{l,t}$ is the contrail frequency index when guiding aircraft at level l to aircraft at level l'. The contrail reduction is

$$\Delta CFI^{l'}_{l,t} = CFI^{l}_{l,t} - CFI^{l'}_{l,t}. \tag{12}$$

Note that when $l' > l$, not all aircraft have the ability to fly from level l to level l'. If altitude level l' is higher than an aircraft's maximal flight altitude, it stays at level l and is not counted in $CFI^{l'}_{l,t}$. In addition, if an aircraft crosses a sector boundary and causes congestion, it stays at level l and does not add to $CFI^{l'}_{l,t}$.

The strategy is to find the smallest element in each column of $\mathbf{CFI}_{center,t}$. If the aircraft are limited to alter Δl levels, the solution is the smallest element in $[CFI^{l-\Delta l}_{l,t} \dots CFI^{l}_{l,t} \dots CFI^{l+\Delta l}_{l,t}]^T$ in each column. The solution is denoted as $[l'_1 \dots l'_{11}]$. Each l'_i means aircraft at flight level i is flying at level l'_i. If $l'_i = i$, the aircraft at level i did not alter.

In order to determine whether the contrail reduction strategy is feasible in the presence of severe weather, a weather severity matrix is used, defined as

$$\mathbf{WSI}_{center,t} = \begin{bmatrix} WSI^1_{1,t} & WSI^1_{2,t} & \dots & WSI^1_{11,t} \\ WSI^2_{1,t} & WSI^2_{2,t} & \dots & WSI^2_{11,t} \\ \vdots & \vdots & \ddots & \vdots \\ WSI^{11}_{1,t} & WSI^{11}_{2,t} & \dots & WSI^{11}_{11,t} \end{bmatrix}, \tag{13}$$

where

$$WSI^{l'}_{center,l,t} = \sum_{i=1}^{337}\sum_{j=1}^{451} \hat{w}^{l'}_{i,j,t}\hat{a}^{l}_{i,j,t}. \tag{14}$$

The increase of WSI if aircraft flying at level l are altered to level l' is

$$\Delta WSI^{l'}_{l,t} = WSI^{l'}_{l,t} - WSI^{l}_{l,t}. \tag{15}$$

The value helps to determine if it is feasible to alter the aircraft cruising altitude from level l to level l'. If $\Delta WSI^{l'}_{l,t} \leq 0$,that means it is even safer to fly at level l' than at l, therefore the contrail reduction move can be applied. If $\Delta WSI^{l'}_{l,t} > \varepsilon$, where ε is a threshold value, the contrail reduction move might not be feasible because of the increase of weather impact. Further analysis is needed to determine the value of ε.

As an example, the CFI matrix for Kansas City Center at 8AM EDT on April 23, 2010 was computed,

$$\mathbf{CFI}_{ZKC} = \begin{bmatrix} \mathbf{0} & 0 & 0 & \times & \times & \times & \times & \times & \times & \times \\ 0 & \mathbf{0} & 0 & 0 & \times & \times & \times & \times & \times & \times \\ 0 & 0 & \mathbf{0} & 0 & 0 & \times & \times & \times & \times & \times \\ \times & 0 & 0 & \mathbf{0} & 0 & 0 & \times & \times & \times & \times \\ \times & \times & 29 & 47 & \mathbf{98} & 230 & 100 & \times & \times & \times \\ \times & \times & \times & 17 & 51 & \mathbf{124} & 39 & 32 & \times & \times \\ \times & \times & \times & \times & 39 & 101 & \mathbf{23} & 16 & 0 & \times \\ \times & \times & \times & \times & \times & 91 & 18 & \mathbf{15} & 0 & 0 \\ \times & \times & \times & \times & \times & \times & 14 & 6 & \mathbf{0} & 0 \\ \times & \times & \times & \times & \times & \times & \times & 7 & 0 & \mathbf{0} \end{bmatrix}. \tag{16}$$

Assume that the aircraft are allowed to move one level (2,000 feet) up or down to reduce contrails formation. All the aircraft between 33,001 feet and 35000 feet (level 5) have the total CFI of 98 ($\mathbf{CFI}_{ZKC}(5,5) = 98$). Moving the aircraft to level 4 will result in 0 in CFI ($\mathbf{CFI}_{ZKC}(4,5) = 0$), a 98 reduction. Other contrail reduction moves include moving aircraft from level 6 to 7, 7 to 8 and 8 to 9. The solution is expressed as [1 1 1 1 4 7 8 9 9 10], resulting in a contrail reduction from 260 to 125, a 51.9% reduction. If the aircraft are allowed to move two levels up or down, it can achieve more reduction. The moves include moving aircraft from level 5 to 4, 6 to 4, 7 to 9 and 8 to 9. The solution is expressed as [1 1 1 1 4 4 9 9 9 10], resulting in a contrail reduction from 260 to 20, a 92.3% reduction.

To evaluate the impact of severe weather, WSI matrix was computed,

$$\mathbf{WSI}_{ZKC} = \begin{bmatrix} \mathbf{1} & 2 & 3 & \times & \times & \times & \times & \times & \times & \times \\ 1 & \mathbf{2} & 3 & 3 & \times & \times & \times & \times & \times & \times \\ 1 & 2 & \mathbf{3} & 3 & 0 & \times & \times & \times & \times & \times \\ \times & 2 & 3 & \mathbf{3} & 0 & 12 & \times & \times & \times & \times \\ \times & \times & 3 & 2 & \mathbf{0} & 4 & 1 & \times & \times & \times \\ \times & \times & \times & 2 & 0 & \mathbf{4} & 1 & 0 & \times & \times \\ \times & \times & \times & \times & 0 & 0 & \mathbf{1} & 0 & 0 & \times \\ \times & \times & \times & \times & \times & 0 & 1 & \mathbf{0} & 0 & 0 \\ \times & \times & \times & \times & \times & \times & 1 & 0 & \mathbf{0} & 0 \\ \times & \times & \times & \times & \times & \times & \times & 0 & 0 & \mathbf{0} \end{bmatrix}. \tag{17}$$

For the case that allows aircraft to move two level up or down, the move from level 6 to level 4 results in a CFI reduction of 124 with WSI increased by 8 ($\mathbf{WSI}_{ZKC}(4,6) - \mathbf{WSI}_{ZKC}(6,6) = 8$). If the threshold ε is set to 10, the move is still feasible even with an increase of weather impact. If the threshold ε is set to 0, the move is not feasible. Instead, the aircraft in level 6 will be moved to level 8, resulting in a CFI reduction from 124 to 91 and a WSI reduction of 4. The contrail reduction strategies described in this section incorporates the weather data so that they are feasible in the presence of severe weather.

Data from 24-hour period on April 23, 2010 were analyzed. The Center contrail frequency indices at all altitudes, with and without CIWS percipication information, are shown in Fig. 7. For the day, the difference of CFI with and without CIWS precipitation information among all centers are 14%. As shown in the figure, it has more impact in the centers including Denver (ZDV), Minneapolis (ZMP), Kansas City (ZKC), Chicago (ZAU) and Memphis Center (ZME). The effect of cloud coverage on computing contrail frequency index is significant and should not be ignored.

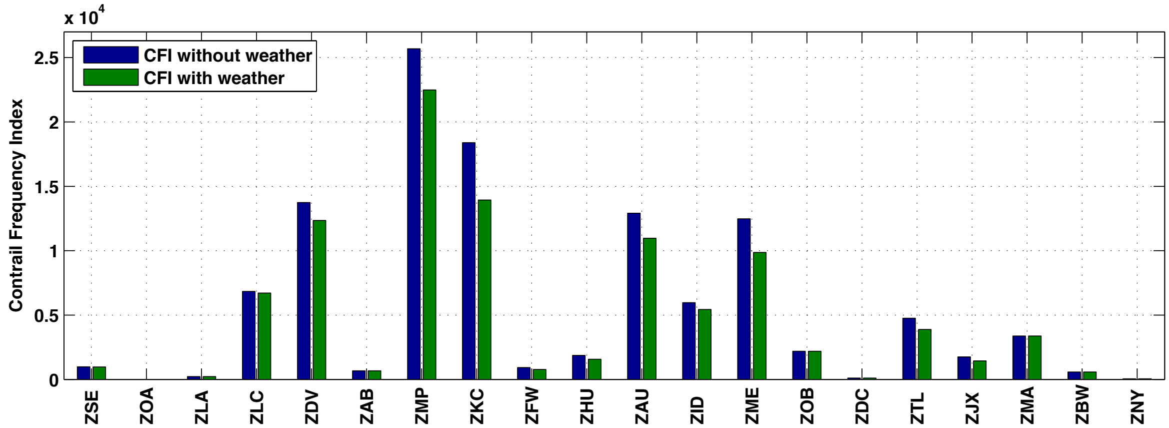


Figure 7. Total contrail frequency index with and without weather information on April 23, 2010.

Next, the contrail reduction strategies were applied using the CFI with weather information and WSI threshold $\varepsilon = 0$. The results are shown in Fig. 8. The center CFIs with weather information before reduction are shown in green bars. When the aircraft are allowed to alter 2,000 feet, the center CFIs after reduction are shown in light green bars. The total reduction among all centers is 63.7%. When the aircraft are allowed to alter 4,000 feet, the total reduction is 92.6%.

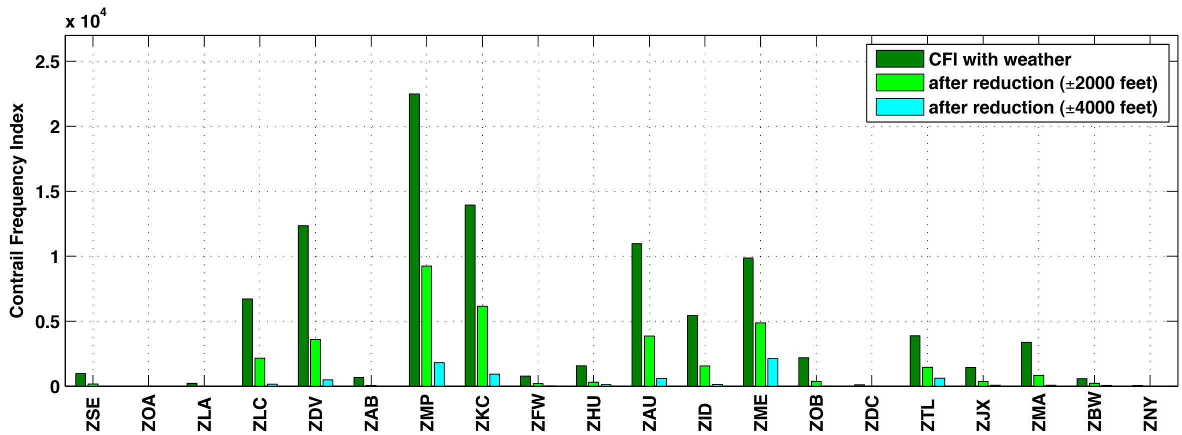


Figure 8. Results of contrail reduction strategies on April 23, 2010.

V. Conclusions

This paper describes contrail reduction strategies using different weather resources. Two weather products were used in this paper, Rapid Update Cycle for the wind, temperature and humidity forecast and Corridor Integrated Weather System for the weather forecast. The two weather products are used in a complementary way to develop contrail reduction strategies. Analysis shows that the contrail favorable regions are correlated with regions with precipitation. During the month of April 2010, there are 53% of CIWS VIL level 1 and above overlapped with contrail favorable regions. For the day tested, adding precipitation weather information reduces the contrail frequency index by 14%. The strategies use the concept of contrail frequency index with weather information to achieve maxima contrail reduction while avoiding severe weather regions. The contrail reductions are achieved by changing the aircraft pre-departure cruising altitudes that would form less contrails. For the day tested, the strategies achieve a 63.7% contrail reduction taking into account the weather impact if the aircraft are allowed to change their cruising altitude 2,000 feet up or down. When the aircraft are allowed to move 4,000 feet up or down, it has a 92.6% reduction. The proposed contrail reduction strategies are suitable for reducing contrail formation in the entire airspace with the presence of different weather conditions.

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