Identification of Flights for Cost-Efficient Climate Impact Reduction

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The aircraft-induced climate impact has drawn attention in recent years. Aviation operations affect the environment mainly through the release of carbon-dioxide, nitrogen-oxides, and by the formation of contrails. Recent research has shown that altering trajectories can reduce aviation environmental cost by reducing Absolute Global Temperature Change Potential, a climate assessment metric that adapts a linear system for modeling the global temperature response to aviation emissions and contrails. However, these methods will increase fuel consumption that leads to higher fuel costs imposed on airlines. The goal of this work is to identify flights for which the environmental cost of climate impact reduction outweighs the increase in operational cost on an individual aircraft basis. Environmental cost is quantified using the monetary social cost of carbon. The increase in operational cost is considering cost of additional fuel usage only. For this paper, an algorithm has been developed that modifies the trajectories of flights to evaluate the effect of environmental cost and operational cost of flights in the United States National Airspace System. The algorithm identifies flights for which the environmental cost of climate impact can be reduced and modifies their trajectories to achieve maximum environmental net benefit, which is the difference between reduction in environmental cost and additional operational cost. The result shows on a selected day, 16% of the flights among eight major airlines, or 2,043 flights, can achieve environmental net benefit using weather forecast data, resulting in net benefit of around $500,000. The result also suggests that the long-haul flights would be better candidates for cost-efficient climate impact reduction than the short haul flights. The algorithm will help to identify the characteristics of flights that are capable of applying cost-efficient climate impact reduction strategy.

I. Introduction

The aircraft-induced climate impact has drawn attention in recent years.[1] To address the aviation environment impacts with the growing air traffic, various methods have been proposed.[2–6] The largest environmental impacts for enroute air traffic comes from emissions of carbon-dioxide and nitrogen-oxides, and persistent contrail formations. It has been shown that commercial aircraft can reduce climate impact due to these factors by modifying their trajectories, although this often comes at the cost of increased fuel

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consumption.[7] Such an increase in fuel consumption represents an increase in the operational cost incurred by an airline.

The three largest environmental impacts for enroute air traffic include direct emissions of greenhouse gases such as carbon dioxide (CO_2), emissions of nitrogen oxides (NO_X), and persistent contrails. CO_2 and NO_X emissions are a function of fuel burn therefore reducing fuel consumption results in emissions reductions. Various procedures have been proposed in the past to reduce the persistent contrail formation, including promising approaches based on changing aircraft flight altitudes. Mannstein[8] proposed a strategy to reduce the climate impact of contrails significantly by only small changes in individual flight altitude. Williams[9, 10] proposed strategies for contrail reduction by identifying fixed and varying maximum altitude restriction policies. However, these restrictions generally imply more fuel burn, thus more emissions. Sridhar,[11] Chen,[12] and Wei[13] proposed contrail reduction strategies by altering an aircraft's cruising altitude in a fuel-efficient way, but these strategies did not address the environmental impact from aircraft emissions. Recently, the Absolute Global Temperature Potential (AGTP), a climate assessment metric that adapts a linear system for modeling the global temperature response to aviation emissions and contrails, was introduced in Ref. 14 and 15 to study the combined effect of CO_2 emissions and contrail formation on the reduction strategies. Chen et al.[7] evaluate both the reduction in environmental cost and the increase in operational costs for the climate reduction strategy by applying the same flight altitude change for all aircraft in each of the twenty U.S. Air Traffic Control Centers. A detailed climate reduction method for individual aircraft was not addressed in that study.

This paper follows the research reported in Ref. 7 and develops an climate impact reduction algorithm for individual aircraft. The goal of this work is to identify flights for which the environmental cost of climate impact reduction outweighs the increase in operational cost on an individual aircraft basis. To determine this, the changes in cost imposed upon both the airlines and society are considered using the cost of fuel and the social cost of carbon[16–18] by developing a trajectory modification algorithm that modifies individual aircraft trajectories. A trajectory modification algorithm has been developed to minimize the aircraft environmental cost by reducing AGTP[14, 15, 19] due to both contrails and CO_2 emissions. The increase in fuel consumption that leads to higher fuel costs imposed on airlines is also computed by the algorithm. This research aims to identify flights that yield the most environmental benefit for the least operational cost from climate impact reduction strategies.

The remainder of the paper is organized as follows. Section II provides a description of the climate impact model, the cost model, and the climate impact reduction method. Next, Section III shows the results and analyses of climate impact reductions for flights from eight different airlines. Finally, Section IV presents a summary and conclusions.

II. Models and Methods

II.A. Climate Impact Model

The climate response to aviation emission and contrails can be modeled as outputs from a series of linear dynamic systems. The carbon cycle models describe the changes to the CO_2 concentration due to the transport and absorption of CO_2 by the land mass and various ocean layers. The Radiative Forcing (RF) for CO_2 emissions is made of a steady-state component and three exponentially decaying components.[20]

Contrails occur at different regions of the earth and add non-uniform sources of energy to the atmosphere. The latest estimates indicate that contrails caused by aircraft may be causing more climate warming today than all the residual CO_2 emitted by aircraft.[21] The net RF for contrails includes the effect of trapping outgoing longwave radiation from the Earth and that of reflecting incoming shortwave radiation from the sun. Energy Forcing (EF) is the net energy flux induced to the atmosphere by a unit length of contrail over its lifetime. Estimates of EF given the RF forcing due to contrails are described in Ref. 22. The EF is expressed as joules/km of contrails.

NO_X increases the amount of ozone in the atmosphere while decreasing the amount of methane in the atmosphere. The amount of ozone produced depends on the lifetime of NO_X that varies from days to weeks in the upper troposphere. The RF associated with NO_X is made up of short-lived positive RF due to ozone and a negative RF due to methane and methane-induced ozone and the combined effect results in a net RF due to NO_X.[23] Research in Ref. 6 shows NO_X has relatively small effect for the climate reduction strategies compared to CO_2 and contrails, therefore its effect is ignored in this paper.

The lifetime associated with different emissions and contrails varies from a few hours to several hundred years. The impact of certain gases depends on the amount and location of the emission, and the decision-making horizon, H in years, when the impact is estimated. These variations make it necessary to develop a common yardstick to measure the impact of various gases.

Several climate metrics have been developed to assess the impact of the aviation emissions.[24] Using linear climate response models, the Absolute Global Temperature Potential (AGTP) measures the mean surface temperature change because of different aircraft emissions and persistent contrail formations.[19] AGTP provides a way to express the combined environmental cost of CO_2 and NO_X emissions, and contrails as a function of the fuel cost. For simplicity, the RF due to contrails is assumed to be independent of the location of the contrails. The near surface temperature change ΔT for each flight can be approximated as

$$\Delta T = \Delta T_{CO_2} + \Delta T_{Con}, \tag{1}$$

where ΔT_{CO_2} is the contribution to AGTP from CO_2 emissions in Kelvin (K) and ΔT_{Con} is the contribution to AGTP from contrails in K. ΔT_{CO_2} is a linear function of the additional CO_2 emissions and ΔT_{Con} is a linear function of the contrail formation time. The coefficients of the linear functions, also known as pulse AGTP, depend on the linear models for RF, the specific forcing because of CO_2, energy forcing because of contrails, energy balance model and the duration of the climate effect horizon.[14] Using the coefficients described in Ref. 6, at the time horizon of H, Eq.(1) can be rewritten as

$$\Delta T^H = \mathrm{AGTP}^H_{CO_2} E_{CO_2} + \mathrm{AGTP}^H_{Con} L_{Con}, \tag{2}$$

where ΔT^H is the temperature changes due to both CO_2 and contrails for the time horizon of H in K, $\mathrm{AGTP}^H_{CO_2}$ is the coefficient of AGTP due to CO_2 for the time horizon of H in K/kg, AGTP^H_{Con} is the coefficient of AGTP due to contrails for the time horizon of H in K/km, E_{CO_2} is the amount of CO_2 emissions in kg, and L_{Con} is the contrail length in km. A list of pulse AGTP coefficients used in this paper is shown in Table 1.

Table 1. Pulse AGTP values for CO_2 and contrails for three different time horizons

Time Horizon	H = 10 years	H = 25 years	H = 100 years
$\mathrm{AGTP}^H_{CO_2}$, K/kg	6.0×10^{-16}	6.7×10^{-16}	5.1×10^{-16}
AGTP^H_{Con}, K/km	1.5×10^{-13}	3.0×10^{-14}	5.1×10^{-15}

The details of the fuel burn, emissions, and contrail models are described in Ref. 12. The details of the climate model can be found in Ref. 6.

II.B. Cost Model

The total social cost of fuel consumption is comprised of the private cost of paying for fuel, borne by airlines and in turn their passengers, and the external cost of environmental damage, borne by societies, present and future. The social cost of carbon (SCC) is the cost, in monetary terms, to society of emitting an additional metric ton of carbon dioxide. It is often used to determine how much investment should be undertaken in order to mitigate the effects of carbon dioxide emissions. It also represents the theoretical value of a carbon tax for a perfect market. This is particularly suitable because asking or requiring airlines to increase fuel costs to reduce contrail formation would be a form of tax on contrail-induced environmental damage. The United States Government combines results from the three most prominent climate models to determine a suitable measure for the social cost of carbon and recently adopted a value of \$36 United States Dollars (USD) in 2007 dollars, which is equivalent to \$41 USD in 2013 dollars.[25] This is the value used for the purpose of this research. Fuel costs historically represent as much as 33% of aircraft operating costs with an increasing trend. The fuel cost for individual flights are likely to increase if otherwise-quasi-optimal trajectories are modified in a way that is detrimental to fuel efficiency so as to avoid contrail favorable regions. For the purpose of this work, the price of jet fuel of \$4 USD per US gallon was used in this paper.

The social cost of carbon can be used to quantify the environmental cost of CO_2 emission. Using the social cost of carbon dioxide as an estimate of environmental cost of CO_2, the additional contribution to environmental cost from CO_2 emissions, $\Delta Cost_{CO_2}$, can be formulated as

$$\Delta Cost_{CO_2} = SCC \cdot \frac{\Delta E_{CO_2}}{1000}, \tag{3}$$

where SCC is the social cost of carbon in dollar per metric ton, and ΔE_{CO_2} is the change in CO_2 emissions in kg. In order to quantify the environmental cost of contrails, the environmental cost of temperature changes, specifically one Kelvin of AGTP, was defined using the SCC and the AGTP coefficient of CO_2 for time horizon H years,

$$ECK^H = \frac{SCC}{1000 \cdot \text{AGTP}^H_{CO_2}}, \tag{4}$$

where ECK^H is the equivalent environmental cost of temperature change in dollars per Kelvin for the time horizon of H years. Assume that the surface temperature is reduced after the climate impact reduction ($\Delta T^H < 0$), the total environmental cost reduction $\Delta Cost^H_{Env}$ can be formulated as

$$\Delta Cost^H_{Env} = ECK \cdot (-\Delta T^H). \tag{5}$$

Note that $\Delta Cost^H_{Env}$ is postive after the climate impact reduction. The environmental net benefit, NB^H_{Env}, is defined as

$$NB^H_{Env} = \Delta Cost^H_{Env} - \Delta Cost_{Opr}, \tag{6}$$

where $\Delta Cost_{Opr}$ is the additional operational cost of applying the climate impact reduction. Only the cost of additional fuel burn is considered as additional operational cost in this paper. If the environmental cost reduction $\Delta Cost^H_{Env}$ is greater than the additional operational cost $\Delta Cost_{Opr}$, the environmental net benefit NB^H_{Env} is positive.

II.C. Climate Impact Reduction

A preliminary trajectory modification algorithm has been developed. The goal of the algorithm is to reduce the total AGTP effect of a flight by modifying its trajectory. Previous study in Ref. 7 shows that the climate effect can be reduced efficiently by applying the same flight altitude change for all aircraft in each of the twenty U.S. Air Traffic Control Centers. This algorithm follows that concept and focuses on modifying the flight profile for individual aircraft; it allows aircraft to deviate no more than one flight level (2,000 feet) above or below the original flight path. It is assumed airlines choose to fly at, or close to, each aircraft optimal operating conditions and, at least approximately, along the most fuel-efficient trajectory, given the weather and traffic conditions at the time of flight. Aircraft can potentially reduce climate impact by avoiding contrail favorable regions either by climbing to a higher cruise altitude of descending to a lower cruise altitude. For most typical commercial aviation cruise altitudes, flying higher will generally yield higher fuel efficiency. However, flight ceiling and mechanical safety constraints often limit aircraft maximum cruise altitudes.

The algorithm evaluates the environmental cost for the period of a flight cruise segment. The total environmental cost is calculated as the combined AGTP effect of CO_2 emissions due to fuel consumption and persistent contrail production caused by flying through contrail regions. The algorithm allows the flight to make one altitude change, meaning climbing 2,000 feet or descending 2,000 feet then returning to the original cruise altitude. The algorithm computes the combined environmental cost and operational cost of all flight segments at the cruise altitude and 2,000 feet above and below it and finds the path that will maximize the environmental net benefit. If this alternative results an environmental net benefit, then the flight path is altered to incorporate this change. Figure 1 shows an example flight modification for one of the flights tested. The grey blocks represent the contrail regions. The contrail regions were computed based on the weather data at the aircraft's take-off time and are assumed to be static during the flight. The blue line is the original flight path and the green line is the new path after modification. As indicated in the figure, the new path tried to avoid the contrail regions by flying 2,000 feet lower than the original flight path. The new path will result in reduction in ΔT_{Con} by avoiding the contrail regions but increase ΔT_{CO_2} due to additional fuel burn at a given time horizon H. The net changes in ΔT^H is negative, meaning the net climate impact is reduced after the flight path modification. The environmental cost reduction $\Delta Cost^H_{Env}$ is increased because of the reduction in ΔT^H, and the operational cost $\Delta Cost_{Opr}$ is also increased because of the additional fuel burn. The net environmental benefit is the difference of the two costs. If the environmental cost saving is greater than the additional operational cost, it will result in environmental net benefit

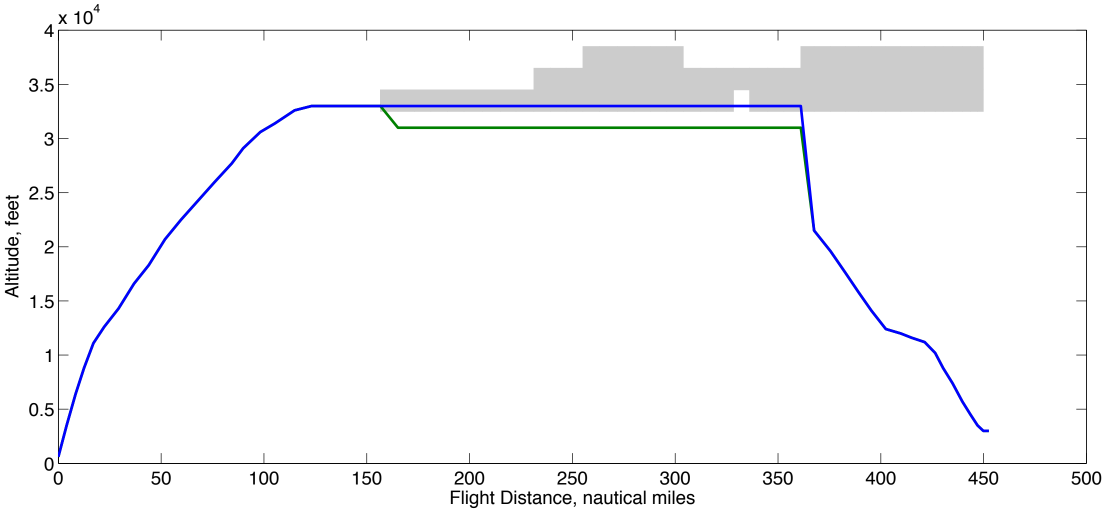

Figure 1. Flight profile (blue line: baseline, green line: after reduction) and contrail regions (grey areas) on April 23, 2010.

In reality, it is not possible to know the exact contrail regions to avoid before flying. The forecast data is required to predict the contrail regions so that the algorithm can determine the path to reduce the climate impact. Using actual weather data in the algorithm is like having perfect forecast data, which is not realistic. Figure 2 shows the same example of flight modification with the predicted and actual contrails regions. The grey blocks represent the contrail regions and the black grid blocks represent the predicted contrail regions. The predicted contrail regions were computed based on the one-hour weather forecast data at the aircraft's take-off time for the entire flight. The algorithm modified the flight trajectory based on predicted contrail regions, and use the actual contrail regions to determine the actual environmental cost. The blue line is the original flight path and the green line is the new path after modification. As indicated by the green line, because of the inaccuracy in the forecast data, the flight would fly through some contrail regions then lower the altitude before it reaches the black grid blocks. The flight would also fly back to the original cruise altitude after the predicted contrails regions is clear of contrails but the actual contrails still exist. It would still result in reduction in environmental cost but the benefit would be reduced because of the inaccuracy in the forecast data.

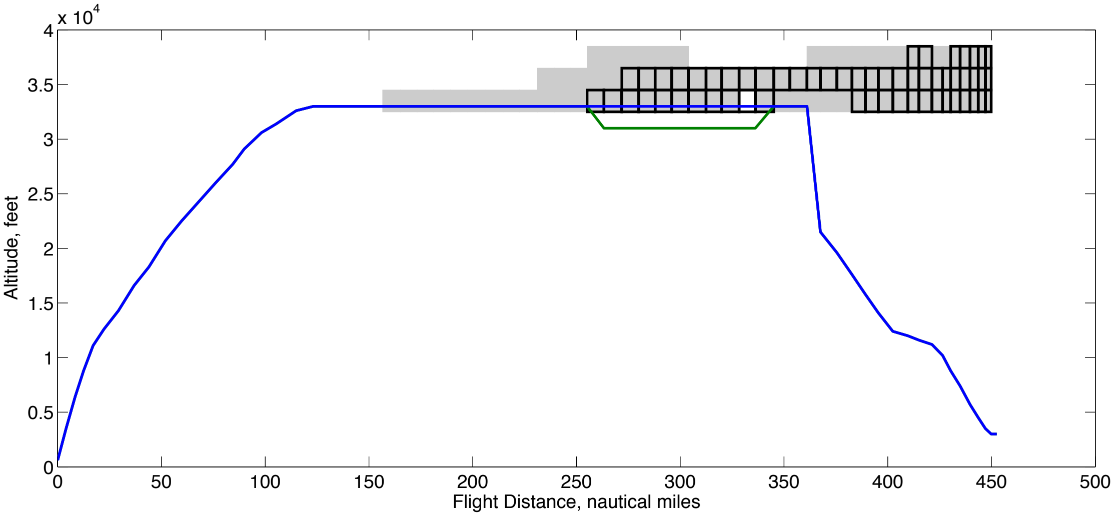

Figure 2. Flight profile (blue line: baseline, green line: after reduction), actual contrail regions (grey areas), and predicted contrail regions (black grids) on April 23, 2010.

III. Results

III.A. Using actual weather data

The trajectory modification algorithm analyzed 12,787 flights using actual flight track data from the Enhanced Traffic Management System of April 23, 2010. These are all flights carried by one of eight major US airlines that operated the most flights on the day: American Airlines (AAL), America West Airlines (AWE), ExpressJet Airlines (BTA), Delta Airlines (DAL), American Eagle Airlines (EGF), SkyWest Airlines (SKW), Southwest Airlines (SWA), and United Airlines (UAL). The contrail model uses atmospheric temperature and humidity data retrieved from the Rapid Updated Cycle (RUC) data, provided by the National Oceanic and Atmospheric Administration (NOAA). The actual and one-hour forecast data based on the take-off time were used to find the contrail regions along each flight path. The day was selected because there were large portions of US airspace covered by the contrail regions. A time horizon of 25 years was used in the climate model; the study in Ref. 7 shows that the environmental benefit after applying the climate impact reduction strategy for time horizon of 25 years is more significant than for time horizon of 50 and 100 years. Figure 3 shows the additional operational cost (the fuel cost increase in this paper), against the environmental cost reduction using actual weather data for the flights with positive net benefit for each airline, in descending order of total net benefit, after the reduction strategy. Each blue dot represents a flight with net benefit (when the environmental cost reduction is greater than operational cost) greater than zero. From a policy perspective, the most desirable flight modifications reduce the net environmental cost by the most while increasing the fuel cost by the least, as these will result in the greatest net benefit. Graphically, these points can be found in the bottom-right corner of the figure. In the figure, Airlines #1, #2, and #3 have a similar pattern. They show more blue dots at the bottom-right corner, while Airlines #4, #6, #7, and #8 show a similar pattern with less blue dots than the others and most of the dots are on the lower of the left-half side. This is mainly because Airlines #1, #2, and #3 have more long-haul flights that will benefit more from climate impact reduction by avoiding long contrails. Airlines #4, #6, #7, and #8 have more short-haul flights therefore the environmental cost reduction of each flight is smaller. Airlines #4, #6 have more blue dots than Airlines #7, and #8 simply because they have more flights during the day. Airline #5 has many short-haul flights and also some long- haul flights therefore the plot is a mix of the two patterns. These observations are consistent with the findings in Ref. 26. The climate impact reduction algorithm was able to achieve a net benefit for 3,067 of the 12,787 flights (24%). The total net benefit is $843,416, or equivalent to a reduction of around 20,000 tons of carbon emissions. The net benefit per flight is $275. Among the 3,067 flights, there are 77 flights resulting in net benefit greater than $1,000. The total net benefit among the 77 flights is $95,482, or $1240 per flight. These flights could be the most cost-efficient candidates for applying the climate reduction maneuver. The results for each of the eight airlines are summarized in Table 2. In the table, it shows Airline #3 has the highest percentage of flights resulting in net benefit, at 43.1% even though the total net benefit is not the highest. This is because Airline #3 has more long-haul and less short-haul flights than the others. Airlines #1 and #2 are next at 29.0%, then Airline #4 at 24.3%. The other four airlines, which have mostly short-haul flights, have percentages less than 20%. This suggests long-haul flights would be better candidates for climate impact reduction than the short haul flights.

Table 2. Number of flights and net benefit (NB) before and after climate reduction algorithm using actual weather data

Airline	total flights	with NB	%	total NB	NB per flight	NB > $1000	total NB
#1	2290	665	29.0%	$202,901	$305	29	$34234
#2	1801	522	29.0%	$147,772	$283	7	$8101
#3	1035	446	43.1%	$141,684	$318	22	$30236
#4	1706	415	24.3%	$105,976	$255	8	$9362
#5	1212	237	19.6%	$69,685	$294	5	$6042
#6	2159	340	15.7%	$63,912	$188	3	$3778
#7	1141	220	19.3%	$58,305	$265	2	$2318
#8	1443	222	15.4%	$53,181	$240	1	$1401
Total	12787	3067	24.0%	$843,416	$275	77	$95482

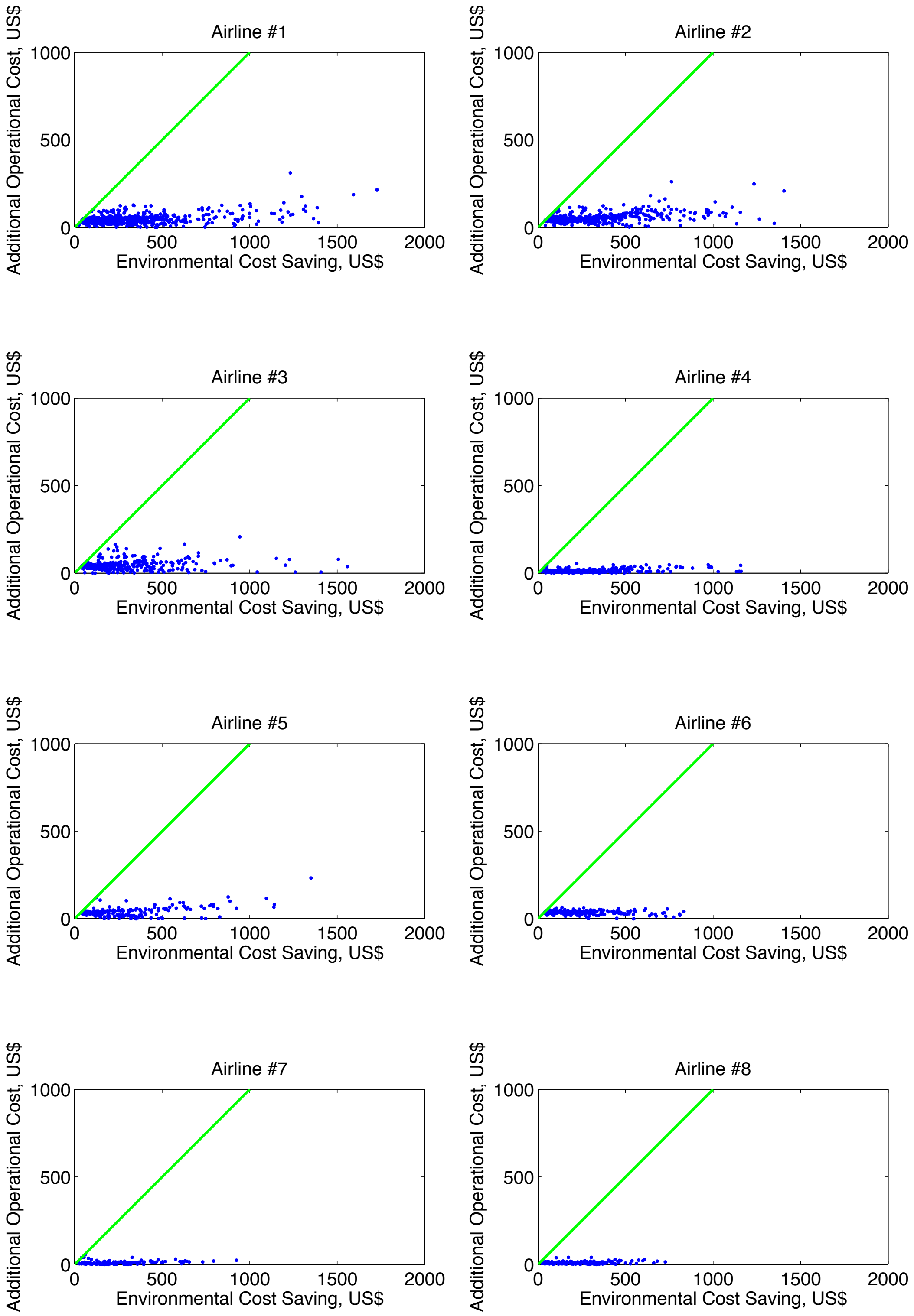

Figure 3. Additional operational cost versus the environmental cost reduction for the flights with positive net benefit using actual weather data on April 23, 2010.

III.B. Using forecast weather data

In reality, it is not possible to know the exact contrail regions to avoid before flying. In this subsection, the one-hour forecast data based on the flight take-off time were used to predict the contrail regions. The climate reduction algorithm used the predicted contrail regions to modify the flight trajectories and used the actual weather data to compute the environmental cost reductions. Because of the inaccuracy in the forecast data, the performance of the climate reduction algorithm was reduced. Figure 4 shows the same example in Fig. 3 using forecast data for the algorithm. Because of the inaccuracy in the forecast data, it is possible that the flights would fly through some contrail regions or would climb or descend without contrail regions present, therefore resulting in lower environmental net benefit or even negative net benefit. It can be seen in the figure that the blue dots were shifted toward the left side compared to the blue dots in Fig. 3. The red dots represent the flights with negative net benefit, where the increases in the operational costs are larger than the environmental cost reductions. The flights with negative net benefit are the group of flights with small environmental cost reduction using actual data (bottom-left corner in Fig. 3). Only applying the algorithm to flights with large net benefit (blue dots on the right side) would avoid negative net benefits.

Using the one-hour forecast data, the climate reduction algorithm was still able to reduce the net benefit for 2,043 of the 12,787 flights (16%) on the selected day; the algorithm identified 2,959 flights for climate reduction and 916 of them ended up with negative net benefit because of the inaccuracy of the forecast data. Also, among the 3,067 flights that could have received net benefit if actual weather data were used, 515 of them were not identified for a maneuver using forecast data. The total environmental net benefit was reduced from $843,416 to $499,256 when using forecast data compared to knowing the actual weather condition, which is a 41% reduction. The net benefit per flight for this one day was $169. The results for each airline are summarized in Table 2. Using weather forecast data, Airlines #1, #2, and #3 still result in the most total net benefits among the eight airlines, mainly because the three airlines have mostly long-haul flights. Airline #3 remains having the most net benefit per flight. As indicated in the table, inaccurate forecast data have significant impact on the performance of the climate reduction algorithm for all airlines.

Table 3. Number of flights and net benefit (NB) before and after climate reduction algorithm using forecast weather data

Airline	total flights	identified flights	with neg. NB	missed flights	total NB	NB per flight
#1	2290	674	235	139	$121,351	$180
#2	1801	497	145	81	$85,901	$173
#3	1035	435	128	65	$90,672	$208
#4	1706	388	87	48	$68,721	$177
#5	1212	215	60	29	$40,522	$188
#6	2159	306	125	69	$27,576	$90
#7	1141	231	67	53	$35,155	$152
#8	1443	213	69	31	$29,358	$138
Total	12787	2959	916	515	$499,256	$169

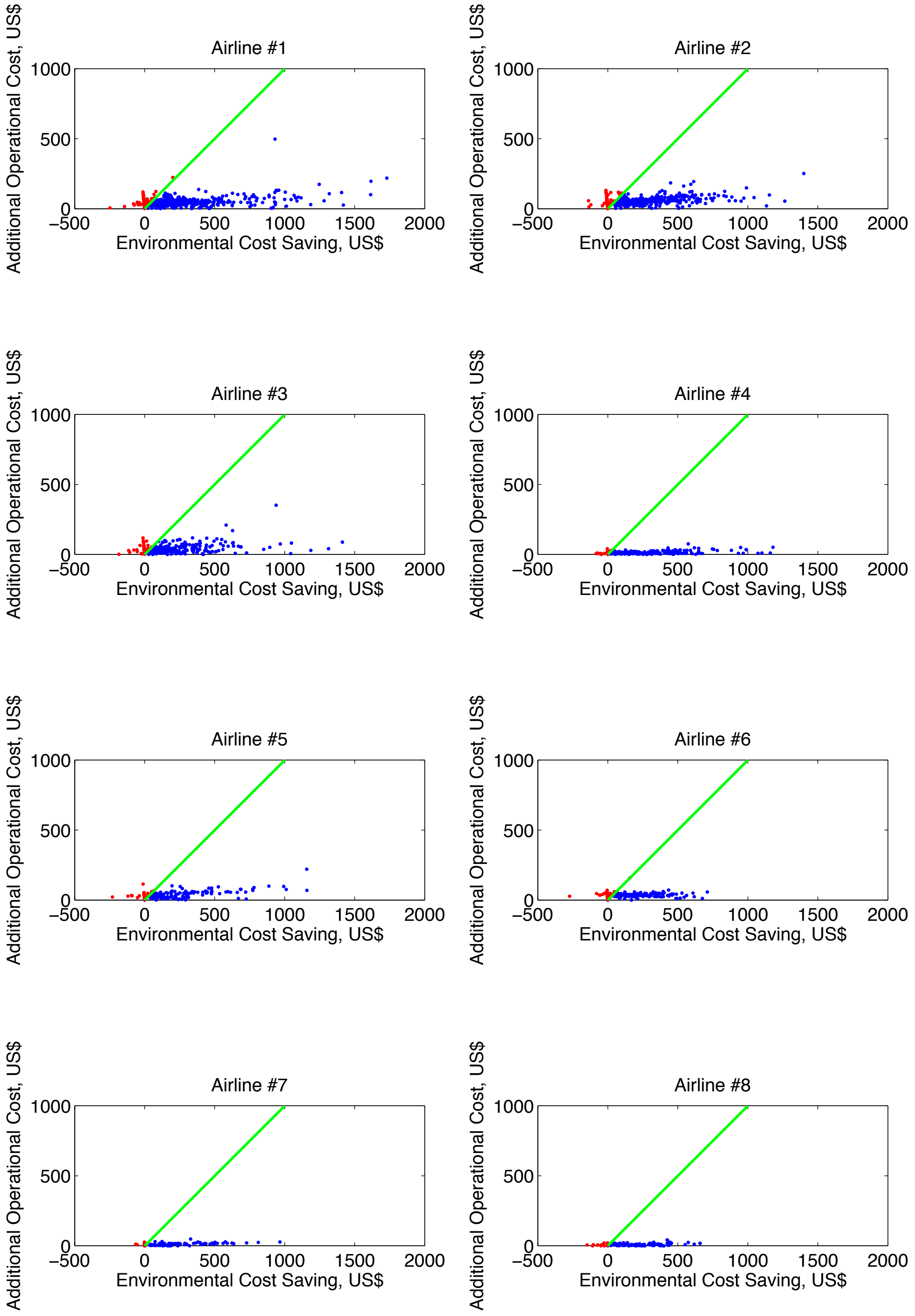

Figure 4. Additional operational cost versus the environmental cost reduction using forecast weather data on April 23, 2010.

IV. Conclusions

A algorithm has been developed that modifies the trajectories of individual flights to evaluate the effect of environmental cost and operational cost of flights in the United States National Airspace System. The algorithm identifies flights of which the environmental cost of climate impact reduction outweighs the increase in operational cost on an individual aircraft basis and modifies their trajectories to achieve the maximum environmental net benefit, which is the difference between the reduction in environmental cost and the additional operational cost. The result shows on a selected day, 24% of the flights can achieve environmental net benefit using actual weather data and 16% of the flights can achieve environmental net benefit using weather forecast data, resulting in net benefit of around $840,000 and $500,000, respectively. It also suggests that the long-haul flights would be better candidates in cost-efficient climate impact reduction than the short haul flights. Future work of this study includes using a more detail contrail model,[27] designing more operational viable routing, and update the actual and forecast weather data along the flights.

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