METHOD FOR CALCULATING NET RADIATIVE FORCING FROM CONTRAILS FROM AIRLINE OPERATIONS

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1 Abstract:

Condensation trails are long, thin clouds that are generated under certain atmospheric conditions by jet engine aircraft and can persist for up to 5 hours. These clouds are highly transparent to shortwave radiation and marginally transparent to outgoing longwave radiation, the net effect is anthropogenic (i.e. human made) enhanced atmospheric greenhouse warming.

This paper describes a comprehensive methodology for modeling the presence and duration of contrails, and the resulting net radiative forcing given a flight profile, atmospheric conditions, and fuel burn/ CO_2 emissions. The model is described and a case study of the combined effect of Radiative Forcing (RF) produced by CO_2 and the cirrus contrail. Results show the trade-off between RF induced by the CO_2 resulting from trajectory changes to reduce RF from contrails.

1 Introduction

The world is now more connected than ever and demand for air travel continues to grow. The International Civil Aviation Organization (ICAO) estimates the airline industry in 2017 has 1,400 commercial airlines and 4,130 airports. This industry served almost 3.5 billion passengers in 2015 through its 34 million departures. 9.5 million of those departures took place in the US alone[1].These flights all generate engine exhaust placed directly in the Troposphere that can, under the right atmospheric conditions, result in condensation trails (i.e. contrails).

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.

These high and thin clouds 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, but reflect a fraction back to the surface adding to the shortwave energy. The overall effect is therefore to enhance atmospheric greenhouse warming [2].

The 1999 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 [3]. In the 2013 report "Anthropogenic and Natural Radiative Forcing" [4] the IPPC revised its estimates and "elevated the potential impact of contrails." It is now accepted as human-made contribution to climate change.

Prior research has shown that contrail formation can be mitigated by modifying flight altitude [5]; generating in exchange a tradeoff between contrail formation and fuel burn and its CO2 emissions. Strategies to manage persistent contrail formations include economic options such as carbon trading or carbon cap schemes. Other options have involved technological developments such as new engine and airframe technologies, and operational changes such as continuous decent approaches [6]. Gierens reviewed various strategies for contrail avoidance [7]. Mannstein proposed a strategy to reduce impact by small changes in individual flight altitudes [8]. Chen N, Sridhar, B**.** suggested a strategy to reduce persistent contrail formation while accounting for extra emissions and air space congestion [9]. Campbell , Fichter [10] describes a method using onboard contrail detection system and fight rerouting. Others limit the flight altitude by introduce a maximum altitude restriction policy.

Because existing flight cruise altitudes and flight plans are optimized to minimize fuel burn, changes to the flight level (FL) will typically result in increased fuel burn and CO_2 emissions. To understand the impact of CO_2 and Radiative Forcing (RF) have on climate it is necessary to measure each contribution by using the climate impact of the individual factors.

This paper describes a model to calculate fuel burn, CO_2 emissions, contrail formation and radiative forcing for a given flight path and given atmospheric conditions. A case study for a flight from ATL to ANC is provided to demonstrate the model.

This paper is organized as follows: Section 2 describes prior models for contrail and CO_2 estimation. Section 3 provides a background on Radiative Forcing. Section 4 describes a Contrail Tradeoff Model and the Data Sources used. Section 5 presents case study for application of the model. Section 6 provides conclusions and future work.

2 Previous Work

This section summarizes the functions used for CO_2 and Radiative Forcing (RF) estimation (Table 1).

Sridhar et. al. (2013) [11] simulated the flight trajectories of 287 flights in U.S. airspace using FACET. For atmospheric conditions they used an ISSR on one day (4/10/2012) derived from NOAA RUC data. The NOAA weather information is based on RUC 13 km data which provides a three dimensional grid of 337 by 451 with 10 altitudes between 26,000 and 44,000 ft. The model is scoped between 26,000 ft and 44,000 ft with 2,000 ft increments (the 37 isobaric levels are interpolated to 2000 ft increments). The analysis sets limits on altitude. The lower limit is set to 26,000 ft as it would typically be too warm for contrails to form and the upper limit is set 44,000 ft as most aircraft will stay below this altitude. To quantify contrail activity the model defines Contrail Frequency Index (CFI) which is used as a measurement. Fuel burn and emissions are based on Euro-controls Base of Aircraft Data Revision 3.7 [12]. Then Contrail regions are estimated at all 20 US air traffic control centers

Chen / Sridhar (2012) [13] perform an analysis of the future air fleet to estimate the climate impact as a pulse AGTP measuring the change in global temperature at a particular time t due to an instantaneous disruption at t0. The study uses RUC weather data assuming contrail formation at r_{contr}<=RHw<100% and Rhi >=100%. Fuel burn is modeled with BADA and CO2 estimated as $1.83X10^{-15}$ $Wm^{-2}kg^{-1}$. The effect of contrails is accounted for using a Contrail Frequency Index CFI.[12]

Gao / Hansman [14] model the trajectories of flights for 11 city pairs using PIANO –X . The atmospheric data is derived from NOAA RUC data.

TABLE 1: Summary of components in contrail analysis models

Model	Fligtpaths	Atmospheric Conditions	Fuel	Contrail Formation	CO2	RF for CO2	Contrail Persistence	Contrail Spreading	RF for Contrails	Notes
Sridhar Chen 2013[]	287 flights in U.S. airspace. April 12, 2010	Future Air Traffic Management Concepts Evaluation Tool (FACET) FACET Predictions	Simulated AEDT / BADA	Relative humidity with respect to ice greater than 100% from RUC Files	Emissions modeled through Boing Fuel Flow Method 2 (BFFM2)	Based on Ref 23	?	Can spread up to 10 times linear contrail.	Estimate 10 to 80 m W/m2 in 2005	
Chen /Sridhar 2012[]	US Future projected traffic	NOAA RUC 13X13 km	Modeled with BADA	rcontr<=RHw<100% and Rhi >=100%	Modeled with BADA	$1.83X10^{-15} Wm^{-2}kg^{-1}$	?	?	Contrail Frequency Index	Climate impact calculated as pulse AGTP.
Gao	12 City Pair	NOAA North American Regional Reanalysis-A (NARR-A) & RUC	Project Interactive Analysis and Optimization (Piano-X)	Satellite observations	Piano-X - Boeing FFM2 - ICAO1 kg jet fuel produces 3.16 kg CO2	Absolute Global Temperature Change Potential (AGTP)	?	Provided by NASA	[3.3, 10, 30] mW/m2	AGTP valuation in Kelvin per nautical mile of contrail . Values generated by NASA Ames
Kaiser	Amsterdam Schiphol (EHAM) to Salzburg (LOWS) . 19 Jan 2012	ISSR in 3 of 5 weather stations along route	Simulated ETPM	ice saturation e*ice = 6.112e^(22.46Th /272.62+Th)	?	$3.785\ 10^{-11}$ $W/(m^2\ tCO2)$	?	?	$6.26\ 10^{-9}$ $W/(m^2$ hr contrail)	Enhanced Trajectory Prediction Model (ETPM)

Fuel consumption is modeled per aircraft type within PIANO-X. The fuel burn is converted to CO_2 considering 1kg of fuel produces 3.16 kg of CO_2. Contrail generation is simulated based on regions identified by NASA. The model uses Absolute Global Temperature Change Potential (AGTP) as a unit to compensate the climate effect over time. The AGTP valuation in performed in Kelvin / nautical mile of contrail generated as [3.3, 10, 30] mW/m2 (with a time horizon of 25, 50 and 100 years). Values were generated by NASA Ames Model.

Chen , Sridhar, B. note that there is a need for a better understanding of the tradeoffs between contrails and emissions to understand the impact on the climate and fully utilize this class of contrail reduction strategies. In [13] Chen , Sridhar, B. use the same approach to weather as in [15]. This effort focuses on the range of the flights, and how they plan to fly, to create a contrail reduction strategy. Flights are segmented into short, medium, long and transcontinental. After analyzing one month of data they find that due to their low altitude, short distance fights (< 500 miles) contribute the least to contrail reductions. Medium-distance flights (500 to 1000 miles), contribute the most to contrail reductions due to the combination of their altitude and volume of flights. Long-distance (1000 to 1500 miles) and transcontinental flights had a more varied result. The analysis concludes that for the top three contrail days in April, 2010, the contrail frequency index per 1,000 miles for medium-range, long-range, and transcontinental flights can be reduced by an average of 75%.

Kaiser et. al. [5] present an Enhanced Trajectory Prediction Model (ETPM) which takes into account the combined effect of RF produced by CO_2 and Contrails. They model a flight from Amsterdam Schiphol (EHAM) to Salzburg (LOWS) on Jan 19th 2012 and run alternative flight paths through the model using weather conditions that produce contrails in 3 of the 5 stations along the route. RF for CO_2 and Contrails are estimated as CO_2 RF = 3.785 10-11 W/(m2 tCO2) and Contrail RF = 6.26 10-9 W/(m2 hr contrail)

Campbell [9] provides a model to avoid persistent contrail formation focusing on the fuel burn. To better estimate the change in fuel burn a quadratic cost function is introduced. The project used a sample trajectory from O'Hare International to Los Angeles International. Contrail conditions are simplified to RH > 100% and determined based on NOAA RUC files, by estimating the RH based on environmental temperature. Aircraft performance is simulated with characteristics of medium-range aircraft such as the Boeing 737 and Airbus A320 with the following restrictions. The analysis finds that while mixed-integer quadratic programming is far more computationally expensive than mixed-integer linear programming, it produced a more efficient trajectory and therefore is a viable option to optimize aircraft trajectories to avoid persistent contrail formation, yielding a 2.76% increase in fuel burn avoiding contrail formation.

This paper complements the prior models by providing a methodology to evaluate the combined RF of Contrails and CO_2 that can be used for *any* flight path aided by RUC weather data. The methodology combined accumulated weather data and recent Contrail RF modeling to estimate the contrail formation and persistence to estimate the Contrail RF.

3 Radiative Forcing:

Radiative Forcing (RF) is the net energy change on the Earth's atmosphere due to some perturbation. RF is used to measure the change prior to industrial era (i.e. 1750) to present-day. RF is typically measured as the change at the top of atmosphere (TOA) in Wm^{-2}.

There are several natural sources of RF: (1) solar irradiance, (2) volcanic forcing, and (3) asteroid impacts. During the period analyzed (1750 – 2012) no major asteroid impacts have occurred so this factor is not considered. The volcanic forcing is dramatic and highly episodic. Solar irradiance is the dominant source of RF. The IPCC estimates the RF of the sun at the Top of Atmosphere between 1750 and the present at 0.12 Wm^{-2} with a range of estimates from 0.06 to 0.30 Wm^{-2}[ref].

Anthropogenic sources of RF affect forcing agents in the atmosphere and on land surfaces. A large number of Green House Gases (GHGs) have had a substantial increase over the Industrial Era, some of which are exclusively of anthropogenic origin. Human activity has also modified the land and changed the surface albedo.

Gases and aerosols have been added to the atmosphere either directly or as a secondary product from chemical reactions. Unlike water vapor, the lifetimes of these different forcing agents can be lengthy and vary substantially. The best estimate today for the total anthropogenic RF over the industrial era is of 2.4± 0.6W m–2, and according to the IPCC "*It is virtually certain that the anthropogenic RF is positive*". The latest estimates find that the RF is 50% higher compared to estimates of AR4 (2005) due primarily to reductions in estimated aerosol RF but also to continued growth in greenhouse gas and a greater uncertainty due to its inclusion of additional impacts on clouds.

The combined effect of well mixed green house gases (WMGHGs) was estimated in AR4 (1750 to 2005) to be 2.63 W m–2 where the four most important gases were CO2, CH4, dichlorodifluoromethane (CFC-12) and N2O in that order. [4]

3.1 RF due to Contrails and Contrail-Induced Cirrus

Contrails net radiative forcing is the result of the change in divergence of solar and infrared radiation fluxes within and below the contrail in the upper troposphere (Liou et al., 1990; Strauss et al., 1997; Meerk Otter et al., 1999 [16].

The area below a contrail has shown a change in heat source in the order of 0.3 K/day for 100% cover. Sassen (1997) [17] found a reduction of solar radiation of 40 W m^{-2} when measured locally in the shadow of contrails.

When the contrail is located above a thick lower level cloud, the atmosphere is heated only above the lower cloud; the heat source is essentially zero below the lower cloud.

During the day, the radiative forcing by contrails is positive however it is strongest during the night because of the absence of negative SW forcing.

The role contrails play in climate has been elevated in AR5. In its evaluation during AR4 the IPCC assessed the RF of contrails as +0.01 (–0.007 to +0.02) W m–2 and provided no estimate for contrail induced cirrus. In AR5, the new estimate of RF due to contrails is set to +0.01 (+0.005 to +0.03) W m–2 and an Effective Radiative Forcing (ERF) is estimated to combine contrails and contrail-induced cirrus to +0.05 (+0.02 to +0.15) W m–2.

The overall effect of subsonic aircraft was estimated in the Aviation and the Global Atmosphere, Special Report of IPCC [3] to be 0.05 Wm^{-2} in 1992 and expected to grow to 0.19 Wm^{-2} by 2050, this includes the combined effect of carbon dioxide, ozone, methane, water vapor, contrails, and aerosols, but do not take into account possible changes in cirrus clouds.

Other estimates of contrail induced RF have been made; for example Wilcox et al. (2012) [18] estimated a contribution from civilian aircraft in 2005 of 0.0009 (0.0003 to 0.0013) W $m^{–2}$ with high confidence in the upper limit.

In 2011 Ulrike Burkhardt and Bernd Kärcher [19] estimated that contrail coverage over the US exceeds 1% with coverage over the eastern corridor even higher. They estimate a net RF 0f .0375Wm^{-2} with areas over eastern US and central Europe reaching over 0.3Wm^{-2}. They classify that contrail induced radiative forcing as "one of the largest single aviation-related radiative-forcing components". They estimate the contrail-cirrus radiative forcing offset by the natural-cloud feedback to yield a radiative by contrail induced cloudiness (CIC) of about 31 mW $m–^{2}$.

The potential impact contrails could have on the environment has triggered multiple efforts. These efforts have used a reduced set of data focusing either on specific high days or routes; which facilitates the evaluation of the methods. The analysis of a full year of data suggests that the conditions to create ISSR change significantly day by day and at each altitude. This leads suggests there is benefit to analyzing the specific flight path an aircraft will take to predict contrail formation. This effort attempts to find alternative flight altitudes for all US flights during a day and estimate contrail formation to predict the RF impact of the flights would have as the combined effect of cloud cooling, warming and CO2.

4 Contrail Model and Data Sources

This section describes the model used to calculate the Net Radiative Forcing from contrails, the Net

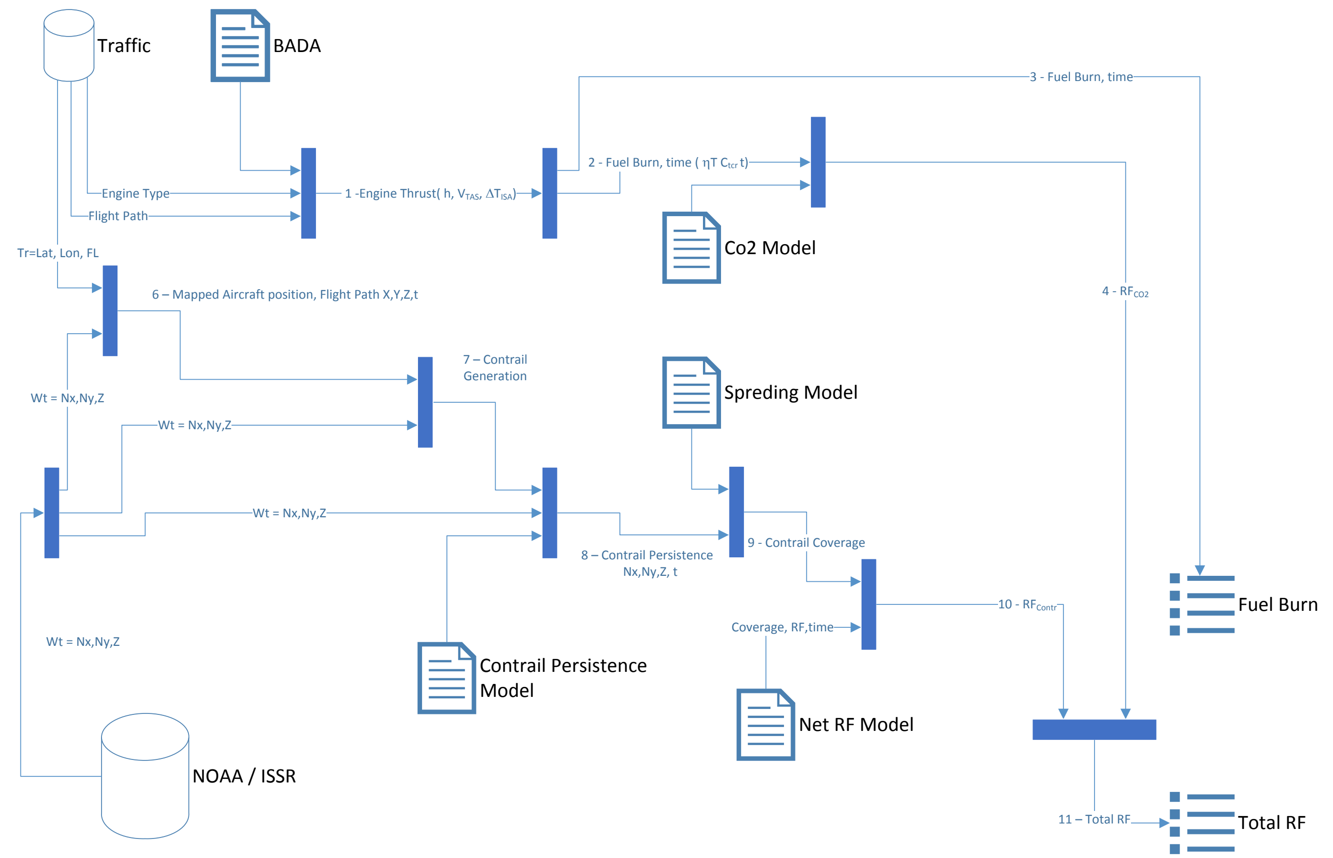

Figure 1: Contrail Induced Radiative Forcing Model

Radiative Forcing from CO2 and the Fuel Burn given a flight path and atmospheric conditions.

4.1 Contrail Model

The Contrail Model, illustrated in Figure 1, calculates the total net Radiative Forcing for a given flight trajectory and atmospheric conditions. The model uses two main inputs; a flight path and weather information.

4.1.1 Flight Path

The flight path used is expressed as a sequence of locations identified by latitude, longitude and altitude and time over the duration of the flight.

4.1.2 Weather Information and ISSR Conditions

NOAA Rapid Refresh Products (RAP), Regional – CONUS, 130 is used. The data is available in a GRIB (General Regularly-distributed Information in Binary form) file through the National Climatic Data Center (NCDC). 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.

Regions where contrails can form 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.

Relative Humidity (RH) is not explicitly provided and is estimated using vapor saturation tables and specific humidity. From the table, –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.

To simplify location, the weather information is kept as provided in the weather information as Nx, Ny, Z. It is then necessary to locate the flight within the weather grid. For this purpose a reference table is created which contains all Nx, Ny combinations along with the range of latitude and longitude that fall within each region.

4.1.3 Fuel/CO2 induced RF

Fuel/CO2 induced RF is calculated from Engine Thrust that is converted into Fuel Burn, that is converted into RF

1. Engine Thrust:

The flight path is used to calculate engine thrust as using Eurocontrol's Base of Aircraft Data Revision 3.6 [12]

Jet:

$$(T_{max})_{ISA} = C_{Tc1} \left(1 - h/C_{Tc2} + C_{Tc3}\, h^2 \right)$$

Turboprop:

$$(T_{max})_{ISA} = C_{Tc1} \left(1 - h/C_{Tc2} \right) / \left(V_{TAS} + C_{Tc3} \right)$$

Cruise Thrust is by definition equal to drag (T = D) The maximum cruise thrust can be calculated as

$$(T_{cruise})_{max} = C_{Tcr}\, T_{Max\ climb}$$

where C_{Tcr} is uniformly set to 0.95

2. Fuel Burn:

Based on the Engine Thrust, Fuel Consumption is estimated based on the Eurocontrol's Base of Aircraft Data Revision 3.6 [12]. The Nominal fuel flow for climb in [kg/min] can be found by multiplying the specific fuel consumption by Engine Thrust T:

$$F_{nom} = \eta\, T$$

Where

Jet:

$$\eta = C_{f1} \left(1 + (V_{TAS} / Cf2)\right)$$

Turboprop:

$$\eta = C_{f1} \left(1 - (V_{TAS} / Cf2)\right) \left(V_{TAS} / 1000 \right)$$

Where

η in [hg/min/kN]

V_{TAS} in [knots]

Cruise fuel flow is adjusted with a cruise fuel flow factor f_{fcr} :

Jet / turboprop:

$$f_{cr} = \eta\, T\, f_{fcr}$$

Descent fuel flow can be found as:

Jet / turboprop:

$$f_{min} = C_{f3} \left(1 - h/C_{f4}\right)$$

3. RF induced by CO_2

Emission of CO_2 can then be calculated using the same equation used in the FAA Aviation Environmental Design Tool (AEDT):

$$CO_2[g] = 3155\ FB[kg]$$

Where CO2 is in grams and fuel burn in kg. The impact on RF from CO2 is estimated as 0.028 W/m^2 (Lee 2010 [20])

$$RF_{FuelBurn} = 0.028 * CO_2[g].$$

4.1.4 Mapped aircraft position

The flight path positions are mapped to the same grid as the weather information. Each location is assigned the unique Position identifier. With the mapping completed the traffic information is swept locating the aircraft position within the mapping and assigning the Position identifier to each record.

To facilitate altitude matching, a minimum and maximum pressure is assigned to each flight level and then assigned a Z_Val from the weather data.

The last variable: time, is provided at the top of each hour within the weather data. For simplicity the minutes and seconds are truncated from the traffic data leaving both traffic and weather data in Hours.

Subsequent processes will only require three integers to locate the flight, a Position Identifier, a Z_val and the hour.

4.1.5 Contrail Generation

The aircraft position is evaluated in the weather information to see if ISSR conditions (temp <= -40C and RH >= 100%) were present at the time. If the atmospheric conditions for contrail formation are present a contrail will be assumed to form.

4.1.6 Contrail Persistence

The contrail can persist and grow if the environment is supersaturated with respect to ice [21] (Jensen 1998). The expected duration of Contrails is up to 5 hours. The model assumes the contrail persists up to five hours as long as the ISSR conditions remain uninterrupted at the location.. When the ISSR conditions are not present, a majority of the contrails last only a few minutes and are not counted in this analysis.

4.1.7 Contrail Coverage

If the contrail meets the persistence criteria it can spread. Contrails spread both vertically and horizontally. Freudenthaler (1995) [22] estimated the lateral growth of contrails to range between 18 m / min and 140 m / min while the vertical growth was estimated at 18 m /min. At these rates a contrail would expand no less than 1 km per hour. This analysis will use the growth rates specified in Table 2

Table 2: Contrail Growth

Time	Width	Crystal Diameter
HH	500m	10µm
HH+1	1000m	20µm
HH+2	2000m	25µm
HH+3	3000m	25µm
HH+4	4000m	25µm

4.1.8 Contrail induced RF

Given continued conditions of ISSR the ice crystals forming the contrail are expected continue to grow. Schröder [23] finds the diameter of the crystals to grow from approx 1 to 10 µm over the first 30 min after the contrail is formed; after that, the growth slows and stabilizes around D = 30 µm. This determines the RF.

To estimate the radiative forcing (RF) at top of atmosphere (TOA) produced by contrails, a model developed by Schumann [24] is used. The model will use a spherical crystal throughout the life of the Contrail. The net RF can then be calculated as the difference between the incoming solar shortwave radiation and the longwave radiation reflected back to space:

$$RF_{Cont} = RF_{SW} - RF_{LW}$$

Radiative Forcing due to Longwave Radiation:

$$RF_{LW} = [OLR - k_T(T-T_0)$$

$$\{1-\exp[-\delta_\tau F_{LW}(r_{eff})\tau]\} E_{LW}(\tau_c) \geq 0$$

Where the optical depth τ is estimated by integrating the product of the mass extinction coefficient β and ice or liquid water content over altitude. β can be estimated as a function of the effective contrail ice particle radius r_{eff}.

OLR is the outgoing longwave radiation. For this analysis we use OLR = 275 W/m^2

T is temperature in Kelvin.

$r_{eff} = ¾ V/A$ [µm]

Where V is the particle volume and A the mean projected particle cross section area

$$F_{LW}(r_{eff}) = 1-\exp(-\delta_{lr}\, r_{eff})$$

$$E_{LW}(\tau_c) = \exp(-\delta_{lc}\, \tau_c)$$

Parameters k_T, T_0, δ_τ , δ_{lr} are provided in Schumann [24] table 1– page 1396

The Contrail optical depth τ at 550 nm can vary between 0 and 2. Typically an optical depth τ will range from $\tau < 0.3$ for a thin cirrus to $\tau > 1$ in the case of thick cirrus clouds. The optical depth above the contrail τ_c ; ranges from0 to 10. For this analysis we will use the optical depths in Table 3.

Table 3: Conditions for contrail persistence

Time	Width	Diameter	τ	τc
0	0	0	0	0
1	500	10	0.4	0.36
2	1000	20	0.2	0.18
3	2000	25	0.08	0.072
4	3000	25	0.02	0.018
5	4000	25	0.01	0.009

Optical depths based on findings of Karcher (2009) [25]

<u>Radiative Forcing due to Shortwave Radiation:</u>

$$RF_{SW} = -SDR\,(t_A - A_{eff})^2\,\alpha_c(\mu,\tau,r_{eff})E_{SW}(\mu,\tau_c)$$

SDR can be calculated considering the SLR is the solar direct radiation in W/ m^2 and A_{eff} = RSR / SDR (reflected solar radiance / solar direct radiance). S_0 is the solar constant and μ defines the cosine of the solar zenith θ (SZA)

$$\alpha_c(\mu,\tau,r_{eff}) = R_c(\tau_{eff})[C_\mu + A_\mu R'C(\tau')F_\mu(\mu)]$$

$$\tau' = \tau F_{SW}\,(r_{eff})\ ,\ \tau_{eff} = \tau'/\mu$$

$$F_{SW}(r_{eff}) = 1 - F_r\,[\,1\text{-exp}\,(\,-\delta_{sr} r_{eff})]$$

$$R_C(\tau_{eff}) = 1\text{-exp}(-\Gamma\,\tau_{eff}\,)$$

$$R'_C(\tau_{eff}) = \text{exp}(-\gamma\,\tau_{err}\,)$$

$$F\mu(\mu) = [(1\text{-}\mu)^{B\mu} / (1/2)^{B\mu}\,]\,\text{-}1$$

$$E_{SW}(\mu,\tau_c) = \text{exp}\,(\delta_{SC}\tau_C - \delta'_{SC}\,\tau_{c,eff})$$

$$\tau_{c,eff} = \tau_c / \mu$$

μ : cosine of the solar zenith angle (θ) can be found using the current flight latitude as follows:

$$\mu = \cos[\,(\text{latitude}_{tr}\,/60)\,\pi/180]$$

$$\mu = \cos(\theta) = SDR\,/\,S_0$$

$$SDR\ = \cos(\theta)*S_0$$

S_0 = 1,361 Wm-2

Parameters provided: Kt = 1.953, TO = 152, $\delta\tau$ = 0.941, δ_{1r} = 0.21, δ_{1c} = 0.16, t_A = 0.879, Γ= 0.242, Aμ = 0.361, Bμ = 0.709, Cμ = 0.709, Fr = 0.512, δ_{SR} = 0.157, δ_{SC} = 0.157, δ'_{SC} = 0.23

OLR value is based on the OLR recorded by

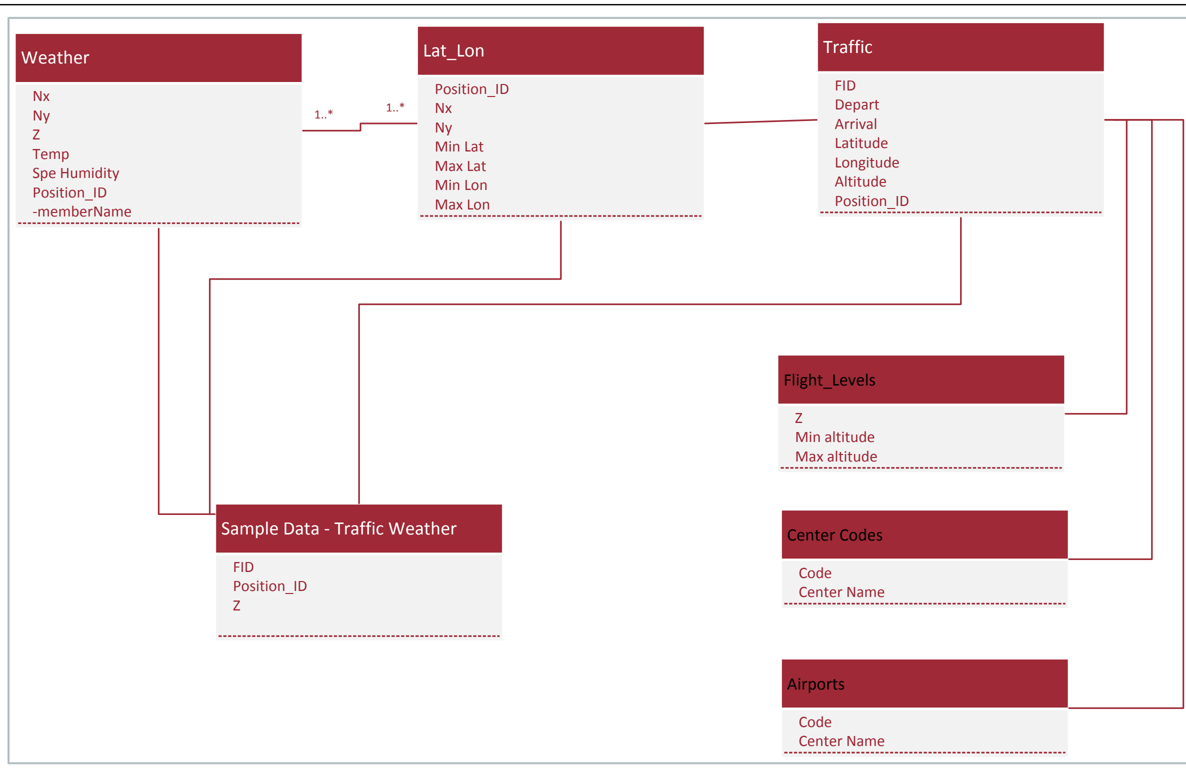

Figure 2: Data Model

NOAA during June 2016. Three sample were extracted to show high and low values. The OLRs sampled corresponded to 329, 194 and 274 W/m^2 . For the purpose of this analysis we will use al OLR or 275 $W/m^{2.}$

4.2 Data Model

The data model is summarized in Figure 3.

Analyzing weather and air traffic data requires dealing with large datasets. The initial analysis shows that weather and traffic data are well related and fit well into a relational database. The data used for the analysis is summarized in Table 4.

Table 4: Sources of data.

Element	Source
Airports	Public
Center Codes	Public
Flight Levels	Generated
Lat Lon	Generated
Traffic	ETMS
Weather	NOAA RAP

1. Airports information including their location, city and country.

a. Center Codes and Names for reference only.
b. Flight Level translation table to convert altitude to a Z_value. The table provides a min and max pressure altitude and its equivalent z_Value.
c. Lat Lon is a translation table to convert latitude , longitude into Nx, Ny coordinates.
d. Traffic information contains records of one sample day of air traffic in the US (26 Jul 2006). This information is provided in a standard latitude, longitude and altitude. The position of the aircrafts is reported regularly.

2. Weather data extracted from NOAA RAP files. The data contains temperature, specific humidity, and pressure at each given position. To discretize the analysis the location, position is maintained in its original Nx, Ny, Z by date and hour.

Consolidating the information in the database enables us to analyze the ISSR regions, compare these to flight records and provide insight to weather impact of alternative flight routes.

5 Validation

To validate the model, a single flight from ATL to ANC was selected and evaluated to estimate the combined Radiative forcing. The traffic information provided 626 records which transformed to 230 weather locations. Contrails were generated in 46 locations during the first hour; 32 during hour 2, 21 during hour 3, 18 during hour 4 and16 locations during hour 5.

5.1 Evaluation process:

5.1.1 Traffic to Weather mapping

Air traffic data is provided in latitude, longitude and altitude whereas weather data is contained in a Nx, Ny, Z matrix. To match the sources we transform the aircraft location to weather notation following the mapping process described in section 4.1.1. Once the aircraft coordinates have been transformed; each traffic record is evaluated to determine if an ISSR was present. If ISSR conditions were present at the time, that location is flagged for contrail generation.

5.1.2 Contrail persistence evaluation

Using the locations identified in the first process, contrail persistence is determined by evaluating each location over the four hours after the aircraft presence. The contrail will be extended at each location during that time as long as the conditions for ISSR remain uninterrupted.

5.1.3 RF estimation from CO2 and Contrail Cirrus

Fuel flow and CO2 are calculated based on Eurocontrol's Base of Aircraft Data (BADA) B737 aircraft adjusted cruise fuel flow. Using the aircraft airspeed and altitude from the traffic data, the fuel flow, CO2 and RF are then calculated as per section 4.1.3. The estimation of RF for contrails is generated taking into account the locations and times where contrails would exist. The set of these locations includes both the time when the aircraft would have traveled and the contrail persistence.

Since the position of the aircraft has been mapped to weather data, it will be found multiple times within the 13X13km area. For this reason the contrail is accounted for only the first time a location is hit.

The calculation of the RF is based on Schumann's model described in section 4.1.8 assuming all crystals as spheres with the following parameters: OLR = 279.6, temp from weather data, contrail width, crystal diameter and optical depth are set depending on the age in hours of the contrail according to Table 2.

The calculation of the RF the model requires multiple parameters and variables. All constants can be obtained in Schumann's RF model or the BADA manual. Other parameters can be established such as the Optical depth, which is calculated based on Karcher's findings [25] and the OLR with was set to 275 W/m^2. Lastly the variables within the model: aircraft location and air speed, ISSR conditions, temperature, cosine of the solar zenith angle (θ), μ are extracted from traffic, and weather data.

5.2 Results.

The calculation of contrail-coverage takes into consideration that the weather data is available in 13 km increments with hourly samples. The results are shown in Table 5.

The hours of Contrail-Coverage1 assumes the contrail is present in full hour increments starting from the first hour. Considering that many contrails are short lived and to help get a sense of the sensibility to hour increments a second scenario is calculated:

Contrail-Coverage2 is calculated reducing the first hour to 15 min and the forth to 30 min. Both calculations assume the contrail in each location to the full 13,000 m length.

With these parameters Contrail-Coverage1 covers an area of 9.06M m^2 vs Contrail-Coverage2 which covers an area of 6.38M m^2 a decrease of 30%. The accumulated RF induced by the contrails adds to 2,511 W/m2.

For the Contrail-Coverage1 and Contrail-Coverage2 the total RF in W was of 14,418 mW and 10,825 mW respectively. The global effect would be of 2.8363 X10^{-5} and 2.1263 X10^{-5} w/m^2.

The total estimated fuel burn added to 15,244 kg or 3,048 kg /hr, producing 47,000 kg of CO_2 and

CONTRAIL_TYPE	Locations	Contrail generating locations	Fuel Burn [kg]	CO2	RF_FuelBurn [W/m2]
Flight	184	-	12,584	39,702,527	1,111,671
Flight	46	46	2,660	8,393,541	235,019
Total	230	133	15,244	48,096,069	1,346,690

Contrail Source	Persistence [hr]	Contrail Widht [m]	Contrail Area [m2]	Locations with Contrail	@ Optical depth	RF_Contrail [W/m2]
Flight	1	500	6,500,000	46	0.40	1,301
Persistence	2	1,000	13,000,000	32	0.20	862
	3	2,000	26,000,000	21	0.08	272
	4	3,000	39,000,000	18	0.02	56
	5	4,000	52,000,000	16	0.01	20
Total Contrail Covarge-hours [m^{2}hr]				133		2,510

Contrail Source	Persistence [hr]	Contrail Widht [m]	Contrail Area [m2]	Locations with Contrail	Contrail Covoagre1 [m2]	Contrail Covoagre2 [m2]	RF Contrail [W] 1
Flight	1	500	6,500,000	46	3,707,379,317	1,444,877,605	4,371,540,360
Persistence	2	1,000	13,000,000	32	2,427,624,564	2,427,624,564	5,199,576,839
	3	2,000	26,000,000	21	1,390,266,344	1,390,266,344	3,163,912,740
	4	3,000	39,000,000	18	702,000,000	702,000,000	1,054,462,286
	5	4,000	52,000,000	16	832,000,000	416,000,000	628,636,626
Total Contrail Covarge-hours [m^{2}hr]				133	9,059,270,225	6,380,768,513	14,418,128,850

Table 5: Sample flight results

induced a RF of 1,346,690 W/m^2.

The global effect of the CO2 would be of 2.63 $X10^{-9}$ w/m^2. The combined RF for the flight is approximately 2.83 $X10^{-5}$ w/m^2

6 Conclusions

This paper proposes a model to evaluate a commercial aircraft's Radiative Forcing impact during a flight. The model uses as inputs the flight path and the atmospheric conditions for the calculation of the induced Radiative Forcing. Fuel Burn and CO_2 are calculated based on the BADA model for a 737 aircraft. The Contrail induced RF is calculated with Schumann's model for RF. The model was validated by running a flight from ATL to ANC. Actual flight and atmospheric conditions were used in the model to calculate fuel consumption and cirrus induced RF. The resulting RF for the flight was 2.83 $X10^{-5}$ w/m^2 .

In contrast with prior models, this proposal focuses on the RF induced by a single flight rather than global RF. To gain insight as to the model's effectiveness we compare generalize the results for the model and assuming 30% of 100,000 flight a day produce this RF, the total RF would be 0.84 w/m^2. The large difference Contrail vs CO2 RF suggests further research is needed to evaluate contrail size, duration and optical depth; however these results do suggest the effect RF produced by contrails far out ways the RF induced by CO_2.

6.1 Next steps:

Prior studies have shown that Contrails can be prevented or triggered by modifying flight paths. The model will be used to evaluate a series of alternative paths and their potential impact in RF.

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8 References

[1] ICAO, Continuing-Traffic-Growth-and-Record-Airline-Profits-Highlight-2015-Air-Transport-Results . www.icao.int/Newsroom/Pages/Continuing-Traffic-Growth-and-Record-Airline-Profits-Highlight-2015-Air-Transport-Results.aspx

[2] Haywood, J. M., et al., 2009: A case study of the radiative forcing of persistent contrails evolving into contrail-induced cirrus. J. Geophys. Res., 114, D24201.

[3] Penner J, Lister D, et al, Aviation and the Global Atmosphere, Special Report of IPCC Working Groups I and III, Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, Published for the Intergovernmental Panel on Climate Change, 1999

[4] Myhre, G., et al, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[5] Kaiser M, Rosenow J, ,Tradeoff between optimum altitude and contrail layer to ensure maximum ecological en-route performance using the Enhanced Trajectory Prediction Model (ETPM), Department of Air Transport Technology and Logistics. Technische Universität Dresden, Germany

[6] Gierens K, et al, A Review of Various Strategies for Contrail Avoidance, Institute of Atmospheric Physics, DLR Oberpfaffenhofen, Germany, The Open Atmospheric Science Journal, 2008, 2, 1-7

[7] Mannstein H, et al, A note on how to avoid contrail cirrus Transportation Research Part D: Transport and Environment. Volume 10, Issue 5, September 2005

[8] Chen N, Sridhar, B. , Tradeoff between Contrail Reduction and Emissions in United States

National Airspace, NASA Ames Research Center, 2012

[9] Campbell S, Neogi N, Bragg M, An Optimal Strategy for Persistent Contrail Avoidance University of Illinois Urbana-Champaign, Urbana, IL, 61801

[10] Fichter, C., S. Marquart, R. Sausen, *and* D. S. Lee *(*2005*)*, The impact of cruise altitude on contrails and related radiative forcing, Meteorol. Z., 14, 563–572.

[11] Sridhar , B. et al, Energy Efficient Contrail Mitigation Strategies for Reducing the Environmental Impact of Aviation, Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)

[12] European Organization for the safety of air navigation. User manual for the base of aircraft data (BADA) 2004. Rev 3.7

[13] Chen N, Sridhar, B. S, Tradeoff between Contrail Reduction and Emissions under Future US Air Traffic Scenarios, NASA Ames Research Center, 2012

[14] Gao H, Hansman J, Aircraft cruise phase altitude optimization considering contrail avoidance. Massachusetts Institute of Technology, 2013

[15] Chen N, Sridhar, B. Tradeoff between Contrail Reduction and Emissions under in the United States National Airspace, NASA Ames Research Center, 2012

[16] R. Meerk Otter, U. Schumann, et al. HAL - Radiative forcing by contrails. Annales Geophysicae, European Geosciences Union, 1999, 17 (8), pp.1080-1094. <hal-00316645>

[17] Sassen Kenneth. Contrail-Cirrus and Their Potential for Regional Climate Change, Department of Meteorology, University of Utah, Salt Lake City, Utah 1997

[18] Wilcox L, et al, Radiative forcing due to aviation water vapor emissions, Atmospheric Environment 63:1–13 · December 2012

[19] Burkhardt U, Kärcher B, Global radiative forcing from contrail cirrus, Nature Climate Change1,54–58(2011)doi:10.1038/nclimate1068 Nature Climate Change 2011

[20] Lee, D, Transport impacts on atmosphere and climate: Aviation. 2010 doi.org/10.1016/j.atmosenv.2009.06.005

[21] Jensen E, Environmental conditions required for contrail formation and persistence. Journal Of Geophysical Research, Vol. 103, No. D4, Pages 3929-3936, February 27, 1998

[22] Freudenthaler, V., Homburg, F. & Jäger, H. Annales Geophysicae (1994) 12: 956. doi:10.1007/s00585-994-0956-9

[23] Schröder F, Kärcher B, On The Transition Of Contrails Into Cirrus Clouds, Journal Of The Atmospheric Science, 1999

[24] Schumann, B; K. GRAF, H. MANNSTEIN. A Parametric Radiative Forcing Model for Contrail Cirrus. Institute for Atmospheric Physics - Ulrich Schumann, Germany . 2012

[25] Kärcher B, U Burkhardt, S. Unterstrasser, and P. Minnis. Factors controlling contrail cirrus optical depth, Atmospheric Chemistry and Physics. 9, 6229–6254, 2009

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