A Primer on Aircraft Induced Clouds and their Global Warming Mitigation Options

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ABSTRACT

Pressure is increasing on all industrial sectors to address climate sustainability, not only for the welfare of the planet, but also for preserving the industry sector's customer base and managing their cost of operations. The aviation industry has a unique opportunity to halve its global Radiative Forcing (RF) contribution by minimizing the generation of Aircraft Induced Clouds (AIC). These anthropogenic (human made) condensation trails create a green-house effect by absorbing or directing back to Earth approximately 33% of emitted outgoing thermal longwave radiation. The effect of AIC accounts for 55% of aviation's total contribution, while aviation CO_2 emissions only account for 39%.

Although AIC is estimated to contribute less than 2% of the Earth's total anthropogenic Radiative Forcing, the effect on global warming is *immediate* (unlike CO_2 emissions which have a two-decade delay in affecting global warming). By reducing AIC now, the aviation industry can cut its contribution to global warming in half. Further, since the effect is immediate, the industry can *buy-time* for longer term CO_2 initiatives in other industries to take effect.

This paper describes the physics of AIC formation and Radiative Forcing (RF) to identify candidate interventions to reduce AIC RF. The analysis identified three intervention opportunities: (1) reduce the quantity of soot generated by kerosene fuel jet engines, (2) reduce or eliminate ice crystal formation, and (3) modify RF properties of AIC. The highest utility and lowest design and implementation costs is to flight plan trajectories to minimize the distance at cruise flight levels in the airspace with atmospheric conditions that are conducive to AIC generation. Other alternatives such as reduced-sulphur kerosene-based jet fuel, drop-in bio and synthetic fuels, require significant investment to scale production. Options such as jet engine designs to reduce soot emissions, alternate fuels such as liquid natural gas and liquid hydrogen, and engine and aircraft designs to reduce fuel burn, require significant research and turn-over of the existing fleets. Fuel additives to suppress ice crystal formation and/or change the RF properties of ice-crystals are still nascent research topics. The implications and limitations are discussed.

Keywords: Aircraft Induced Clouds, contrails, global climate change, global warming, radiative forcing, soot, contrail-cirrus, sustainability

1 INTRODUCTION

"Fly responsibly" is the theme of a recently launched advertisement campaign by KLM Royal Dutch Airlines whereby it asks the flying public "Do you always have to meet face-to-face?" and "Can you take the train instead?" Why would an enterprise challenge their customers decision to purchase their service?

There is increasing pressure on all industrial sectors to address climate sustainability coupled with the realization that failure to address the existential issue of global warming will adversely impact demand and cost of operations. KLM hoped to get ahead of the social media politics of "flight shaming that is forcing politicians and policymakers to address aviation's perceived contribution to global warming. Although aviation's estimated contribution to total anthropogenic global warming is approximately 4%, the emergent social media "flight shaming" has negatively affected demand for travel and choice of vacation destinations. In response, policymakers are proposing regulations such as aviation taxes and regulations to ban domestic flights on routes where other modes of transportation, such as trains, are viable alternatives.

The aviation industry has a unique opportunity to significantly reduce its Radiative Forcing (RF) contribution to global warming, and stay ahead of the politics, social media, and regulations by minimizing the generation of Aircraft Induced Clouds (AIC). Contrary to popular belief, AIC contribute 55% of aviation's total contribution to global warming, whereas CO_2 contributes only 39%. Further AIC can be reduced by operational changes and does not require new technologies.

AIC, also known as "condensation trails," or "contrails," are thin line-shaped ice clouds generated by jet airliners. Jet engines emit water vapor and particles at high altitudes that mix with the cold, low pressure atmosphere resulting in the formation of visible condensation trails. Complex thermodynamic, fluid dynamic and chemical microphysical processes, cause the hot water vapor to condense and freeze on particles left by the engine creating an artificial cloud of ice crystals behind the aircraft.

Under specific atmospheric conditions, known as Ice Super Saturation (ISS), these contrails can grow, spread and persist for up to 10 hours. These long-lived "ice clouds" are defined by the World Meteorological Organization as Cirrus Homogenitus [1] or AIC, and are the *only anthropogenic* (i.e. human-made) clouds.

As is the case for natural formed clouds, AIC impact the natural radiation balance of the Earth. Like high Cirrus clouds, contrails are highly transparent to incoming "solar" shortwave radiation from the Sun (77%) reflecting only 23% back into Space. The clouds also redirect back to Earth, 33% of the emitted outgoing longwave "thermal" radiation. AIC generates a net imbalance of 10% during the day, and 33% at night. This imbalance affects the temperature structure in the lower atmosphere therefore contributing to global warming [2].

The Earth's total anthropogenic radiation balance is estimated at -2.29 W/m^2 of which aviation's contribution is estimated at approximately 3.9% (-0.09 W/m^2) of the total [3]. Within aviation's contribution, *55% (0.050 W/m^2) is derived from Aircraft Induced Clouds*, 39% (0.035 W m^2) from CO_2, and 6% (0.05 W/m^2) from NO_x [4]. This is contrary to popular belief that CO_2 is the main source of global warming from aviation activities.

Whereas the effect of CO_2 and other greenhouse gases on the lower atmosphere temperature structure takes approximately 20 years from the date it is emitted, the effect of AIC is *immediate*. In this way mitigating the effects of AIC on global warming can slow global warming and can buy-time for longer term CO_2 initiatives to take effect.

Since AIC has greater impact than CO_2 (i.e. 55% vs 39%) and the effect of AIC is immediate, policy makers and industry have asked: What is the potential for mitigating contrails through technology advancement or operational changes?

This paper provides and overview of contrails, the "physics" of contrail formation and spreading, cloud properties with respect to Radiative Forcing, and identifying candidate interventions. The analysis, summarized in Figure 2, is used to identify critical physical, chemical, and thermodynamic properties that could be used to intervene in the spreading of contrails including: the number of soot particles emitted by jet engines, the hydrogen content of emissions, jet engine emissions temperature, and location of atmospheric regions conducive to contrail spreading. A ranking of candidate technological and operational interventions is provided.

There is a reasonable scientific understanding of the chemistry of jet fuel combustion and particle generation, and the physics of ice crystal formation from jet engine emissions. The RF impact of AIC, the measurement and calibration of RF, and the impact of RF on the lower atmosphere temperature structure, however exhibits some uncertainty. There are also complex interactions with secondary and tertiary climate effects that are not yet well understood. With this in mind, the purpose of this paper is to assist in guiding the research and developing a set of hedging strategies for all plausible outcomes for contrail mitigation as the scientific consensus on the RF impact is reached.

This paper is organized as follows: Section 2 describes the life-cycle of Aircraft Induced Clouds (AIC). Section 3 provides a high-level description of the thermodynamic, fluid-dynamic, and chemical microphysical processes in AIC formation and spreading. Section 3 also provides an overview of the cloud properties, radiative forcing and global warming. Section 4 describes candidate interventions through technological advances and operational changes to reduce AIC formation. Section 5 provides a portfolio analysis of mitigation options. Section 6 concludes with a discussion on a roadmap to reduce the impact of AIC, and on the limitations of the current scientific understanding of AIC and their impact on Global Warming.

2 LIFE CYCLE OF AIRCRAFT INDUCED CLOUDS (AIC)

There are three types of AIC: (1) short-lived contrails, (2) long-lived persistent contrails, and (3) long-lived contrail cirrus.

AICs are categorized as short-lived with duration less than 10 minutes, and long-lived with durations up to 10 hours (Table 1). Short-lived contrails are line-shaped and have short duration due to ice subsaturated atmospheric conditions that do not sustain contrails. Radiative forcing associated with short-lived contrails is negligible.

Long-lived contrails are split into two categories: Persistent and Cirrus. Persistent contrails remain line-shaped and can be as long as 10 km. They last from 10 minutes for up to 10 hours. Over time, due to non-uniform winds, turbulent (random) motions and humidity fluctuations, persistent contrails lose their initial linear shape and transition into contrail cirrus with irregular shapes. These contrails can overlap and merge with other contrails in traffic-congested areas, forming extended ice cloud layers with non-uniform shapes, depth and duration [7]. The persistent contrails may also merge with or form in natural cirrus [5]. Irregular-shaped contrail cirrus cannot be easily distinguished from natural cirrus hampering their observation. AIC can also be transported considerable distances (e.g. 100 km) away from their location of generation, resulting in AIC presence in locations where ISS conditions are not met [6].

The RF properties of long-lived contrails are a function of the 3-D volume of the clouds and the optical properties of ice crystals in the AIC.

The three AICs are shown in Figure 1.

TABLE 1: Characteristics of Aircraft Induced Clouds

Characteristic		**Short-lived**	**Long-lived**	
Ice Cloud Type		**Contrail**	**Persistent Contrail**	**Contrail Cirrus**
Morphology		Line shaped	Line shaped	Irregularly shaped
Atmospheric Conditions		Ice sub-saturated	Ice Super Saturated	
Duration of Contrails		0-10 minutes	10 minutes – 10 hours	
Dimensions of Cloud	**Depth**	100 m	100 – 1000 m	
	Width	10 – 100 m	100 – 1000 m	<100 km

	Length	0.1 – 10 km	0.1 – 10 km	<100 km
RF Potential		Negligible	0.01 W/m^2 ~ 20%	0.04 W/m^2 ~ 80%

(a) (b) (c)

FIGURE 1 Aircraft Induced Clouds (AIC): short-lived contrail (a), long-lived persistent contrails (b), long-lived contrail-cirrus (c)

3 THE PHYSICS OF AIRCRAFT INDUCED CLOUDS (AIC) FORMATION, SPREADING, AND RADIATIVE FORCING (RF)

The relationship of the aircraft propulsion system that generates the emissions, the ambient atmospheric conditions needed for the formation of contrails, and the parameters that drive RF is shown in Figure 2. In the contemporary aviation system, jet engines burn kerosene-based fuels that generate water vapor and soot particles. In a complex thermodynamic, fluid dynamic, chemical process, the jet engine emissions are mixed with the cold, humid ambient air and form ice crystals. Under ISS conditions the ice crystals can grow and spread creating contrail-cirrus clouds. These clouds impact RF by absorbing, scattering and transmitting incoming short-wave “solar” radiation, and outgoing long-wave “thermal” radiation.

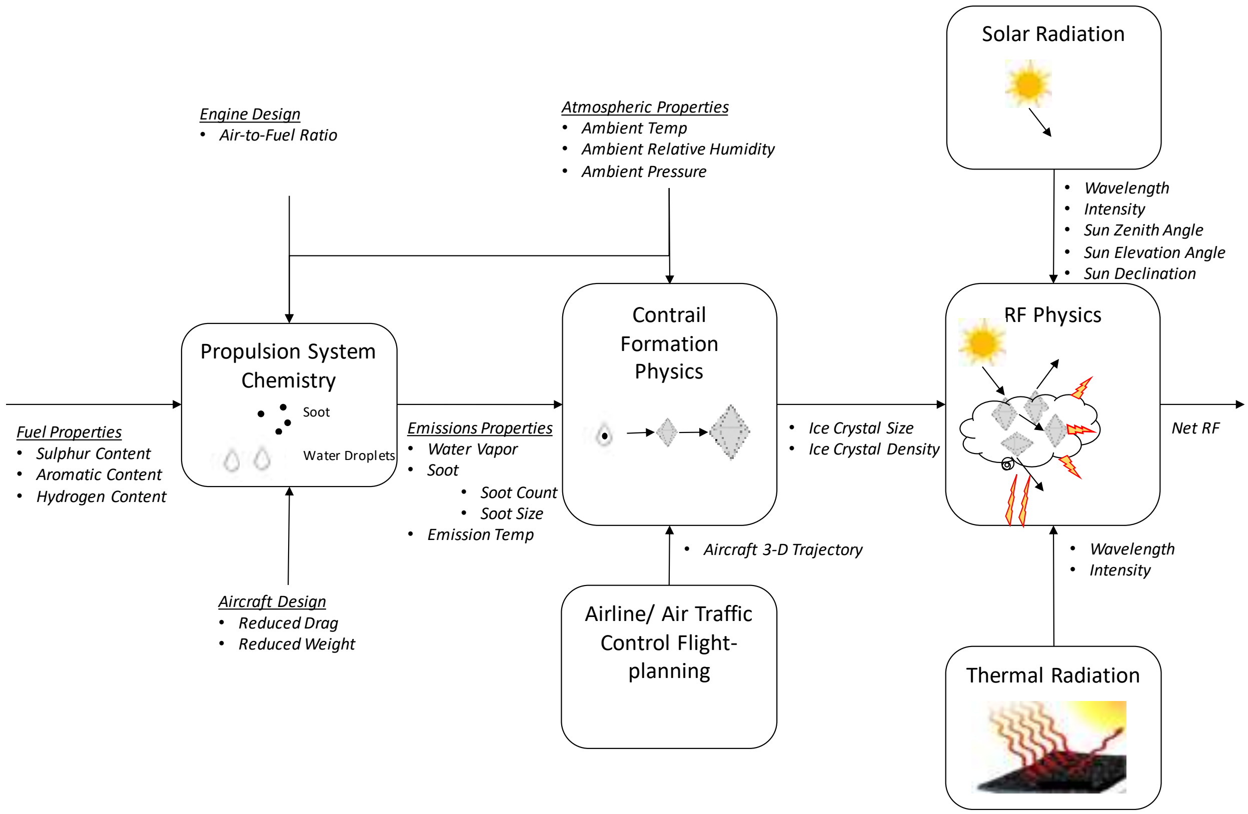

FIGURE 2: Summary of properties that affect contrail formation and spreading and the Radiative Forcing of clouds.

3.1 Jet Engine Chemistry

Jet engine propulsion is achieved from the combustion of oxygen and a hydrocarbon-based fuel leading to the ejection of the resultant hot gases from the rear of the engine. Combustion is a chemical reaction between kerosene and oxygen that yields heat, light, CO_2 and H_2O. Approximately 1.24 tons of water is generated for each ton of kerosene.

$$C_{10}H_{22} + 15.5O_2 \rightarrow 10CO_2 + 11H_2O + 3.76(15.5)N_2 + 10.6kcal/g$$

3.2 Aircraft Induced Cloud Physics

Natural cirrus and AIC (i.e. persistent contrails and contrail cirrus) are high altitude clouds composed of ice crystals that form and spread in Ice Super Saturated (ISS) regions [7]. ISS regions have cold and moist atmospheric conditions relative to ice phase saturation. These regions occur when the movement of continental weather patterns, such as maritime tropical air masses, transport moist air into colder regions

When a jet aircraft transits airspace that is *not* an ISS region, short-lived contrails may form in the drier or warmer (ice subsaturated) air. These contrails are short duration (< 10 minutes), narrow, and do not absorb or reflect RF. When a jet aircraft transits airspace that *does* meet the criteria for an ISS region, long-lived persistent contrails and contrail cirrus form. AIC and natural cirrus clouds are very similar except that AIC has a significantly higher number of ice crystals which results in reflection and absorption of incoming shortwave and outgoing longwave radiation.

There are two main stages of AIC evolution: (1) the Formation Stage, and (2) the Spreading Stage. In the Formation Stage, the initial short-lived contrails form directly behind the jet engines and last for about 10 min [10]. During the Spreading Stage, which follows the Formation Stage, the long-lived and cirrus contrails form (Table 2). The formation of AIC is a complex set of thermodynamic, fluid dynamic and microphysical chemical processes that is beyond the scope of this paper. See [8], [9] for a more detailed description.

TABLE 2: The "physics" of the formation and spreading of AIC

Time	Stage	Phase	Type of Mixing	Physics	Cloud Particle Type	Cloud Ice Crystal Size	Cloud Ice Crystal Shape	Cloud Ice Crystal Density
0 – 0.1 secs	Formation into Contrail for Short-lived and Long-lived Contrail	Jet Regime	Plume mixing and cooling	Exhaust aerosol particles	Water, Soot, Particulates	10nm	Water droplet	
0.1 – 1 secs				Particles activate into water droplets	Water droplets	100nm	Water droplet	> 10,000 per cm^3
1 – 10 secs		Vortex Regime	Wake vortex formation	Water droplets freeze and Ice particles grow	Ice crystals	1000nm	Spherical	
10 – 100 secs				Ice crystals grow in upper wake and sublimate in lower wake	Ice crystals		Spherical	
100 secs – 10 mins					Ice crystals		Spherical	
10 mins – 10 hours	Spreading into Long-lived Persistent Contrail and Contrail Cirrus		Windshear increases contrail coverage	Ice crystals sublimate in warmer ice subsaturated air	Ice crystals	> 30 micro-meters.	Crystal shapes deviate from spherical shape	Turbulent mixing reduces ice crystal density

3.2.1 Formation Stage

Contrails begin to form in the jet regime when jet engine exhaust plumes expand and their constituents mix with surrounding ambient air. When temperatures are below 233° K (≈−40 °C), short-lived and long-lived contrails can be seen behind the aircraft.

Aerosol particles in the jet exhaust plumes cool and interact with condensable vapors of the jet engine emitted water vapor, and the ionized gas molecules. The different particle types compete for the supersaturated vapor to form water droplets. Although water droplets are initially present in contrails, they are unstable in this region of the atmosphere because the upper troposphere stays below liquid water saturation.

The aerosols in this process include emitted soot particles, nanometer-sized (ultrafine) aqueous aerosol particles formed within the plume, and atmospheric particles mixed (entrained) into the plume from the ambient air. Soot particles, which figure most conspicuously in droplet formation, are caused by locally rich fuel-air mixtures within the jet engine combustor primary zone and, to a lesser extent, by high combustor operating pressures. The turbine breaks up some large soot particles while some small particles agglomerate in the exhaust plume to form larger particles. The highest level of soot typically occurs during takeoff and climb out when fuel flows and internal engine pressures are at their peak.

Significant ice nucleation (i.e. ice crystal formation) occurs only after water droplets have formed. The rates of homogeneous (pure liquid) droplet freezing are inversely proportional to the decreasing temperature [11]. In this way, the number of ice crystals formed increases at a faster rate than the drop in the temperature.

Persistent contrails develop further through the circulatory airflow patterns that are generated by the wake vortices from the aircraft wings. The plumes from each of the jet engines merge with the vortices from each wing, forming an inhomogeneous wake.

The continued evolution of ice crystals depends on the interaction between the jet plumes and the wake vortex. The vortex, in which most of the contrail is captured will descend up to 100 m below the aircraft flight level. This downward motion leads to a partial loss of ice crystals due to sublimation in the lower part of the wake. However, the ice crystals present in the upper wake continue to grow by uptake of entrained ice supersaturated water vapor. In this regime the average ice crystal diameters is 1000 nano-meters.

After the contrail has aged a few minutes, the ice crystal size distribution increases with signatures of nucleation, growth and sublimation. Eventually, flow instability triggered by turbulence causes the organized flow pattern to collapse and mix with ambient air thus terminating the formation stage.

3.2.2 Spreading Stage

During the Spreading Stage, turbulent mixing results in a decrease in concentration of ice crystals over time. The ice crystal size increases due to the uptake (deposition) of water vapor from ice-supersaturated layers. Then the sustained deposition growth causes ice crystal shapes (habits) to deviate from their initial spherical isometry. The shapes of the ice crystals - droxtals, hexagonal prisms and columns, bullet rosettes and aggregates - affect the growth in size, fall rates, and optical properties.

Ice crystals with maximum dimensions >30 μm settle (sediment) due to gravity with fall speeds >100 meters per hour and sublimate in warmer or drier air. Smaller crystals remain around the flight levels due to negligible fall speeds as long as some supersaturation can be maintained.

The efficiency of sedimentation depends on the on ice supersaturation, the rate of cooling of air, and on the size, habit and concentration of the ice crystals. Sedimentation increases the height of the AIC, which, in turn, enhances the rate of spreading and therefore coverage in the presence of wind. Sustained warming and drying due to large-scale subsidence (i.e. gradual sinking) dissolves the AIC entirely.

3.3 Radiative Forcing Physics

The Earth's radiation balance is measured at the Top of the Atmosphere (ToA) based on annual averages. The incoming shortwave (SW) radiation from the Sun is absorbed by the Earth and the atmosphere during daylight hours. The Earth subsequently emits outgoing longwave (LW) thermal radiation during the day and the night. When the climate is in balance, the incoming SW radiation is equal to the outgoing LW radiation [2]. Naturally occurring clouds perturb this climate balance by absorbing and reflecting incoming and outgoing radiation [12]. Anthropogenic impacts to the atmosphere such as the

Greenhouse Effect from Green House Gases (e.g. CO_2, methane) and from AIC also affect the climate balance.

Radiative Forcing (RF) is a first-order indicator of the radiation balance and is widely used to quantify climate change [5]. RF refers to initial imbalances over a specified region and period of time. For example, the Intergovernmental Panel on Climate Change (IPCC) uses global averages taken relative to a pre-industrial time (1750). Global RF cannot be observed directly so it is estimated using models and by extrapolation of regional values inferred from satellite observations.

The effect of the RF at the Top-of-Atmosphere (TOA) produced by AIC is composed of the sum of the incoming solar shortwave radiation (RF_{SW}) and outgoing longwave radiation (RF_{LW}) and can be modeled as follows [13]:

$$RF = RF_{LW} + RF_{SW}$$

Where:

$$RF_{LW} = [OLR - k_T(T-T_0)\ \{1-\exp[\delta_\tau\ F_{LW}(r_{eff})\tau]\}\ E_{LW}(\tau_c) \geq 0$$

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

It is beyond the scope of this paper to define all the parameters of this model, however, the key parameters that determine the long-wave radiation are: Optical Depth (τ), magnitude of the outgoing long-wave radiation (OLR), temperature (T), and (soot) particle radius (r_{eff}). For the short-wave radiation, the key parameters are: magnitude of the incoming solar radiation (part of equation for SDR) and the Sun Zenith Angle (a term in the equation for μ).

The RF for clouds is directly determined by the cloud Optical Depth which is a function of ice crystal size and ice crystal density. In a cloud-less atmosphere (Figure 3-a), the radiation balance is maintained. Atmospheric gases and aerosol particles reflect, absorb, and transfer the same amount of incoming radiation as outgoing radiation. However, when greenhouses gases are introduced into the atmosphere a larger percentage of outgoing radiation is reflected back to Earth, resulting in a net warming.

Natural clouds are composed of water or a combination of water and ice crystals (Figure 3-b). Clouds dominated by water droplets form at lower altitudes. These clouds have a net cooling effect by reflecting back into space a higher percentage of incoming radiation.

High altitude clouds are dominated by ice crystals (Figure 3-c). These high ice clouds are optically thin and partially transparent to solar radiation (wavelength ≈ 0.2–4 μm). As a result, they reduce the outgoing radiation (radiant energy with wavelength > 4 μm) released into space via absorption and re-emission of LW radiation at cold temperatures. Also, their ability to scatter SW radiation back to space (known as albedo forcing) is low. The greenhouse forcing effect is stronger for higher and colder clouds with increased density of ice crystals.

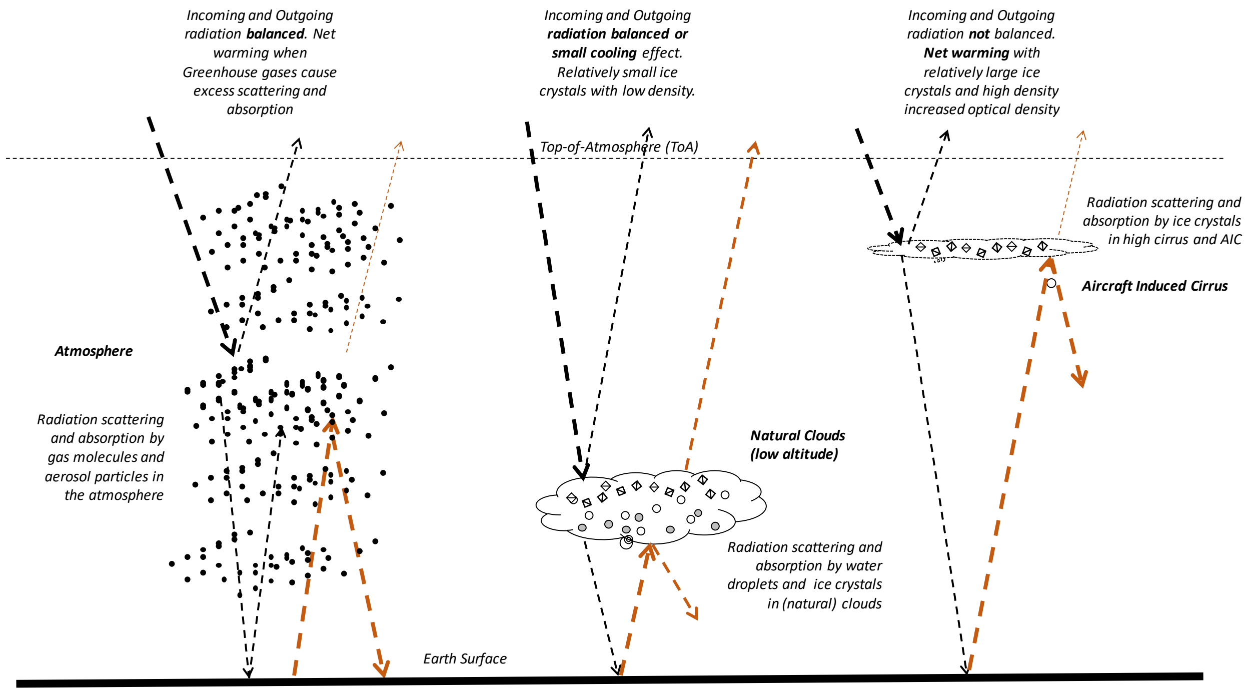

FIGURE 3: Effect on Global Warming of atmosphere (left), natural (low) clouds with water droplets (middle), and high-altitude ice crystal AIC (right)

3.4 Sustained Global Temperature Change Potential (SAGTP)

The Sustained Absolute Global Temperature Change (SAGTP) is a measure of the degree of greenhouse effect [32] that is used to compare alternate sources. This method accounts for the fact that CO_2 does not impact global warming immediately but takes an extended period (e.g. 20 years) before an effect is evident.

SAGTP is obtained by integrating R(τ) over a time period between τ = 0 and τ = α. Where R(τ) is the impulse response function for the surface temperature at time τ.

For AIC the greenhouse effect is a function of the length of the contrails over a period α.

$$SAGTP^{AIC} = \frac{1}{a}\int_0^{\alpha} R(\tau)d\tau$$

For CO_2, SAGTP models the temperature changes due to CO_2 emitted constantly over a period α where AGTP is the absolute global temperature change for CO_2 emission [32]:

$$SAGTP^{CO2} = \frac{1}{a}\int_0^{\alpha} AGTP^{CO2}(\tau)d\tau$$

SAGTP is calculated for a time horizon of α = 25 years, 50 years and 100 years (Table 3). The ratio of SAGTP for AIC and CO2 indicates the significance of AIC relative to CO_2 in the short-term.

TABLE 3: Comparison of the effects of AIC and CO2 over three time periods

SAGTP	Time Horizon in Years		
	α = 25 years	α = 50 years	α = 100 years
$SAGTP^{AIC}(\alpha)$ (Kelvin/kg)	A^{CO2} x 0.3024	A^{CO2} x 0.3223	A^{CO2} x 0.3079
$SAGT^{CO2}(\alpha)$ (Kelvin/km)	1.5522×10^{-13}	8.4377×10^{-14}	4.5003×10^{-14}
$SAGTP^{AIC}(\alpha)/SAGT^{CO2}(\alpha)$ (kg/km)	282.0295	143.8422	80.3083

$$A^{CO2} = 1.82 \times 10^{-15} \text{ (W/m}^2\text{ kg) [33]}$$

4 MITIGATING RADIATIVE FORCING (RF) FROM AIRCRAFT INDUCED CLOUDS (AIC)

As described in the sections above, RF for AIC is determined by the: density of the ice crystals, and the size of ice crystals in the AIC. These two characteristics are the result of: (1) propulsion system chemistry, (2) contrail formation physics, and (3) RF physics (Figure 2) Mitigation strategies for each stage are summarized in Table 4.

Table 4: Opportunities to mitigate Aircraft Induced Clouds

Component	Property	Technology Category	Technology	Notes
Propulsion System Chemistry	Less Soot	Aircraft Design	Reduced Drag	New development and certification. Replace existing fleet
			Reduced Weight	
		Jet Engine Re-design	Air-to-Fuel Ratio	New engine design and retrofit/replace existing fleet
			Combustor redesign	Early phase R&D New engine design and retrofit/replace existing fleet
			Dilution Jets	Early phase R&D New engine design and retrofit/replace fleet
		Drop-In Fuels	Reduced Sulphur kerosene	Limited production capacity
			Bio fuel	Limited production capacity. Currently used with Kerosene blend
			Synthetic fuel	Demonstration stage of R&D. Needs significant increase in production capacity. Currently used with Kerosene blend
	No Soot	Alternate Fuels and Engines	Liquid Natural Gas (LNG)	Engine modifications. Needs fuel distribution infrastructure
			Liquid Hydrogen	Engine modifications. Needs fuel distribution infrastructure
Contrail Formation Physics	No ice crystals	Flight plan based on atmospheric conditions to avoid AIC	Flight planning software	Straightforward implementation by modifying existing operations

		Suppress ice crystal formation	Anti-freeze Fuel Additives	Need to overcome corrosive impact of additives on engine components
RF Physics		Flight plan Overlay on Existing Clouds	Flight planning software	Need to understand frequency of appropriate conditions
		Flightplan Overlay on Existing Contrails	Flight planning software	Need to understand the impact of ice crystals growth, density, and RF of "thicker" AIC
	Reflection, Absorption properties	Optical properties of ice crystals	Size, shape and density of ice crystals	Science of AIC ice crystal formation is poorly understood

4.1 Propulsion System Chemistry

Jet engine emission properties are the first stage in the process, specifically soot count. Several approaches reduce the soot count and eliminate soot count by aircraft design, jet fuel properties and engine design.

4.1.1. Aircraft Design

Soot count can be reduced by burning less fuel and due to reduced aerodynamic drag and reduced aircraft structural weight. One example is the blended wing body that has several efficiency advantages resulting in lower fuel burn and lower emissions [31].

4.1.2 Engine Design

In addition to reducing soot count by improved aerodynamics and aircraft structures, soot can also be reduced by engine design. Two approaches to reduce soot: (1) optimizing the operating condition and configuration of the jet engine combustor to produce less sooty flames, and (2) dilution jets to dilute the mixture and provide oxygen to oxidize the soot [28], [45].

Rich Quench Lean (RQL) combustion minimizes the formation of nitrogen oxides in current combustion chambers [29]. The fuel is first burned with a fraction of the total air to ensure that the lowest count of nitrogen oxides form. The remaining air is then introduced and then "lean burned" in another combustion zone. Any soot that forms in the first zone is oxidized as much as possible in the second zone. This ensures that no pollutants leave the combustion chamber.

In-flight soot emissions can also be reduced by simply burning less fuel. Lean combustion technology that uses high air-to-fuel ratios during fuel combustion can generate low soot particle emissions [30].

4.1.3 Fuel Properties to Reduce Soot Counts

The major combustion products of conventional kerosene jet fuel are CO_2, water vapor, and soot. Soot count in the jet engine emission is *the* most critical parameter with regards to ice crystal formation and the resulting RF impact. There are two categories of fuel property modification: (1) drop-in fuels, (2) alternate fuels

4.1.3.1 Drop-in Fuels

Sulphur and aromatic content of the jet fuel determine the soot count. Kerosene jet fuels can be produced with reduced sulphur levels. Although the reduced-sulphur kerosene has no impact on engine performance, there is evidence of increased in CO_2 emissions (+0.1%) [20].

Synthetic fuels and bio-fuels can be produced to meet industry/regulatory technical and safety standards providing for "drop-in" fuels that replace kerosene-based fuel without any changes to the fuel distribution infrastructure or engines [21]. These fuels contain low levels of sulphur and aromatic species. Synthetic fuels are produced through the Fischer–Tropsch chemical processes from coal, natural gas or biomass. Bio-fuels are generated from feedstock, algae, or biomass.

Pure biofuels significantly reduce soot count, however they are unlikely to bring about a large reduction in AICs in the near term due to limitations in production capacity. As a consequence, kerosene-biofuel blends are typically used. The kerosene-biofuel blend has been shown to reduce soot particle emissions by 50% [22]. The impact on ice crystal numbers however is only −35% [23]. The lower nucleated ice numbers, due to reduced soot particle emissions, are compensated by enhanced sublimation losses.

Kerosene-biofuel blends tend to exhibit a higher hydrogen content relative to conventional jet fuel (+8%) [22] which slightly increases contrail formation threshold temperatures [24] (0.5–1 K). This increases AIC formation but does not lead to a significant increase in ice crystal numbers at the end of the formation stage (<5%) [25].

Pure synthetic fuels are still in the demonstration stage. The use of kerosene-synthetic fuel blends is expected to yield similar results as the blended kerosene-biofuels.

Blended fuels are widely used. The soot count is proportional to the percentage of the bio/synthetic fuel in the blend.

4.1.3.2 Alternate Fuel Sources

Although contemporary commercial jet engines are designed to operate exclusively with aviation kerosene, gas turbine engines can operate with a wide variety of liquid and gaseous fuels. Derivatives of aircraft jet engines are available for marine and industrial applications using natural gas, diesel fuel, alcohol, and other fuels. Future aircraft engines could also be configured to operate with alternative fuels, such as Liquid Natural Gas (LNG) or Liquid Hydrogen (LH2) [27].

Liquid hydrogen (LH2) and liquefied natural gas (LNG, consisting of mostly methane) have zero soot and sulphur emissions. However, both fuels, especially LH2, generate increased water vapor. Super-cooled LNG is condensed from simple methane gas and sells for a fraction of the price of kerosene. In a climate model study, RF due to a hypothetical fleet of LH2-propelled aircraft (cryoplanes) with increased water vapor emissions was lower than that for kerosene aircraft [26].

Due to the limited space on an aircraft, natural gas or hydrogen would have to be stored in liquefied form. Although the energy density of hydrogen by weight is nearly three times that of conventional aviation fuels, the energy density by volume is one-fourth that of conventional aviation fuels. In addition, the potential weight savings of hydrogen fuel is offset by the additional weight of the liquid cryogenic fuel storage and handling systems and associated aircraft structures. The engineering challenges associated with accommodating low-density, cryogenic fuels in aircraft fuel tankage and supply systems are so substantial that their use can probably only be considered in new aircraft specifically designed for such fuels.

Other major impediments, especially with respect to hydrogen, include cost, availability, and infrastructure (for production, transportation, storage, and aircraft servicing). Natural gas is readily available, but hydrogen must be produced. Hydrogen can be produced by releasing and collecting hydrogen from hydrocarbon fuels. This process releases 2 to 4 times more CO_2 than simply using hydrocarbon fuels directly as a jet fuel.

Electrolysis of water can also be used to generate hydrogen. This would require significant electricity not produced by fossil fuels. Burning hydrocarbon fuels to produce electricity to produce hydrogen to replace the use of hydrocarbons as a jet fuel would release more CO_2 than continuing to use conventional hydrocarbon jet fuel.

Full electrification of future generations of aircraft would lead to zero emissions of CO_2, NOx and soot. The transition to electric flight, including long-range routes (e.g. transcontinental), is predicated on batteries with sufficiently high energy density and motors with low weights. Hybrid propulsion systems with jet engines that generate electricity to drive electric motors is another option.

Given the magnitude of these challenges and the long time frame it would take to develop and deploy significant numbers of new commercial aircraft equipped to operate with alternative fuels, it seems highly likely that commercial aviation will be dominated by aircraft powered by conventional jet fuels for the foreseeable future.

4.1.4. Aircraft Operations

Fuel-burn can also be reduced by optimizing operations. Airlines must trade-off time-enroute with fuel-burn. This is captured in the Cost Index, a ratio of time-costs/fuel costs, that airlines determine for each flight based on the desired aircraft utilization and other operational network considerations. A low cost index minimizes fuel-burn, but increases time-enroute.

4.1.5 Reduced Flight Demand

Another option to reduce fuel-burn is a reduction on demand for travel resulting in a reduction of the number of flights. There are several scenarios that could result in this outcome including increased fuel prices, and market-based schemes such as congestion pricing, slot auctions, and cap-and-trade.

4.2 Contrail Formation Physics

Once soot and water vapor have been emitted, very specific atmospheric conditions are required to generate AIC (Figure 2). A feasible mitigation strategy is to develop four-dimensional flight plans for airline, military, and government flights to avoid the ISS regions in the airspace. A case study of one year of flight operations in the contiguous United States (CONUS) identified that an average of only 15% of the flights each day (maximum 34%) generate contrails [14]. Further, the contrail generation is mostly limited to geographic regions of the in south-east/mid-west and on the Pacific coast. A more general study of the atmosphere found that the fraction of the ice supersaturated altitudes in which aircraft actually fly (i.e. below FL430) is relatively small (10–15%) [15].

There are two ways to avoid the airspace with ISS regions: (1) fly around the perimeter, or (2) fly over/under. The horizontal width of ISS regions (>100 nm) makes routing around the ISS region prohibitive. Studies have found that lateral re-routing generated additional fuel burn costs that exceeded the environmental benefit [16], [17], [18].

Flying over the ISS region is a feasible option. A study of aircraft performance found that efficiency penalties are less than 1% when within roughly ±2000 ft of the optimum cruise altitude [19]. A study of one year of flights in the U.S. found that when flights with planned routes through airspace with ISS regions had their Cruise Flight Level increased by 2000’ or 4000’ (if needed) it resulted in an estimated average daily decrease of -63% in NRF with a 2000’ increment in Cruise Flight Level, and an average daily decrease of -92% in NRF with up to a 4000’ increment in Cruise Flight Level [14]. These changes were considered statistically significant when compared to the original Cruise Flight Level at the 99% confidence interval. The difference in fuel burn between trajectories with the original Cruise Flight Level and fuel burn with the incremental Cruise Flight Levels were not statistically significant. Additional fuel burn for climb and descent was counter-balanced by the lower drag at higher altitudes for long duration cruise segments.

This approach to avoid contrails is not new. Military operations frequently fly below or above ISS regions to avoid “conning altitudes” that result in the generation of contrails that provide a visual indication of the location of the (stealth) aircraft to adversaries.

Another alternative is to suppress ice crystal formation. Fuel additives could potentially coat soot particles with a highly “hydrophobic” material to reduce their ability to act as condensation nuclei for water vapor. Research is required to better understand the chemistry and physics of the ice crystal coating. There are also questions on the impact of the additives on engine performance, the corrosive effects of the additives, and environmental implications of the additives [44].

4.3 RF Physics

Once soot and water vapor have been emitted, and the ISS atmospheric conditions are met, the next option is to leverage the properties of radiation. A theoretical, but impractical operational option, is to leverage the effect of the Sun Zenith angle on incoming short-wave RF. The concept would be to shift peak traffic towards sunrise and sunset. This increases the albedo effect of the AIC reflecting a higher percentage of incoming radiation back out to space [19].

Fuel additives may also alter contrail optical properties. However, additional research required to understand the ice crystal formation and the impact of the additives. Questions on the impact of the additives on engine performance, the corrosive effects of the additives, and environmental implications of the additives must be addressed [44].

Other concepts include flight planning over existing clouds to avoid trapping additional thermal radiation. Also using precision navigation to lay contrails on top of each other. The impact on ice crystal formation, density and RF impact need to be studied

5 RANKING MITIGATION OPTIONS FOR REDUCING RF FOR AIC

The AIC mitigation options were assessed based on: Technology Readiness Level (TRL), Effectiveness in reducing AIC, and Deployment Time Frame. Each option was also assessed for Technology Development Costs and Technology Deployment Costs. Table 5 summarizes the assessment for each of the options.

TABLE 5: Ranking Options for Reducing RF for AIC

Mitigation Option								**Utility vs Cost**	
			Utility		**Relative Cost**				
Stage of Process	**Property Mitigated**	**Mitigation Technology**	**Technology Effectiveness**	**Deployment Time Frame**	**Technology Readiness**	**Technology Design Costs**	**Deployment Costs**	**Utility**	**Relative Cost**
Attribute Weights			0.5	0.5	0.33	0.33	0.33		
Propulsion System Chemistry	Less Soot	Lower Drag aerodynamics to reduce Fuel Burn	Low (reduces fuel burn only)	Long (fleet replacement)	High	High (redesign and certify new airframe)	High (fleet replacement)	**1**	**7.1**
		Jet Engine Re-design (air-to-fuel ratio, combustor redesign dilution jets)	High (has potential to significantly reduce soot)	Long (engine replacement or fleet replacement)	Medium	Medium (modify existing engines)	High (engine replacement or fleet replacement)	**6.5**	**6.7**
		Reduced Sulphur kerosene	High (reduces soot)	Now (Drop-in fuel)	High	Low (Drop-in fuel)	Low (change to refining process)	**8**	**2.0**

		Bio fuel Drop-In	Medium (used in kerosene blend, cannot scale production)	Now (Drop-in fuel)	High	Low (Drop-in fuel)	Medium (significant increase in production capacity)	**6**	**2.0**
		Synthetic fuel Drop-In	Medium (used in kerosene blend, cannot scale production)	Now (Drop-in fuel)	High	Low (Drop-in fuel)	Medium (significant increase in production capacity)	**6**	**2.0**
		Blended Bio/Synthetic fuel Drop-In	Low	Now (Drop-in fuel)	High	Low (Drop-in fuel)	Low	**6.5**	**0.7**
	No Soot	Liquid Natural Gas (LNG)	High	Long (fleet replacement, new infrastructure)	Medium	High (design and certify new engine)	Very high (needs new infrastructure)	**6**	**8.2**
		Liquid Hydrogen	High	Long (fleet replacement, new infrastructure)	Medium	High (design and certify new engine)	Very high (needs new infrastructure)	**6**	**8.3**
Contrail Formation Physics	No ice crystals	Flight plan based on atmospheric conditions to avoid ISS Regions	High (may not eliminate all AICs)	Now	High	Low	Low	**7.5**	**0.7**
		Fuel additives to suppress ice crystal formation	Medium	Immediate	Low	High	High	**6.5**	**9.7**
RF Physics	Reflection, Absorption properties of AIC	Flightplan Overlay on Existing Clouds	Medium	Immediate	High	Low	Low	**5**	**1.3**
		Flightplan Overlay on Existing Contrails	Low (reduces fuel burn only)	Immediate	High	Low	Low	**4**	**2.0**
		Reflection, Absorption properties ice crystals	Medium	Immediate	Medium	High	High	**6**	**9.7**

The options can be grouped into two clusters: near-term/low cost and long-term/significant costs (see Figure 4). The most feasible near-term, low cost mitigation option is to manipulate Cruise Flight levels to minimize time in airspace with atmospheric conditions conducive to AIC generation. Operational changes for avoiding ISS regions can be implemented almost immediately, requiring some coordination between airline dispatch and air traffic management. The cost of implementation of the concept is low and the operational cost to the airlines (of additional fuel burn) is considered very low with benefits in good-will from customers.

The next near-term solutions, associated with reduced soot counts, are relatively low cost. Reducing soot emissions can occur through drop-in fuels (sulphur-free kerosene, bio-fuels, and synthetic fuels). Although technologically feasible, these solutions require significant increases in production capacity. Short-term solutions using blended kerosene fuels, reduce soot count by 50%.

Longer-term solutions that require significant investment in R&D, design and certification costs, and deployments costs: improved aerodynamics, engine design to reduce soot emissions, LNG and/or LH2 engines, and fuel additives to suppress ice crystal formation, or modify ice crystal properties.

Improved aerodynamics and reduced aircraft structural weights are beneficial but with a low utility. Reduced soot can also be achieved through engine re-design but there exists uncertainty in the technical feasibility and potentially high implementation costs. Alternate propulsion, such as LNG and LH2, require technology development as well as modification and/or creation of the fuel distribution infrastructure. Along with engine redesign, alternate propulsion and aircraft re-design for low drag there is a long transition period to replace the existing fleet.

Also, in the category of long-term initiatives is ice-crystal suppression and/or ice-crystal property modification through fuel additives. Several approaches to suppress the formation of contrails from the exhaust of a jet engine have been developed. One early approach was the injection of chlorosulfonic acid into the exhaust of an engine to diminish the particle size of water below the visible range. Chlorosulfonic Acid is a corrosive, clear liquid; melting point -80 C; boiling point 151 C; soluble in chlorinated solvents. It is hygroscopic and lachrymatory strongly. It reacts with water to form HCl. It is highly corrosive.

Significant research is required for the basic science of particle coating, as well as impacts on engine component corrosion, and environmental impact.

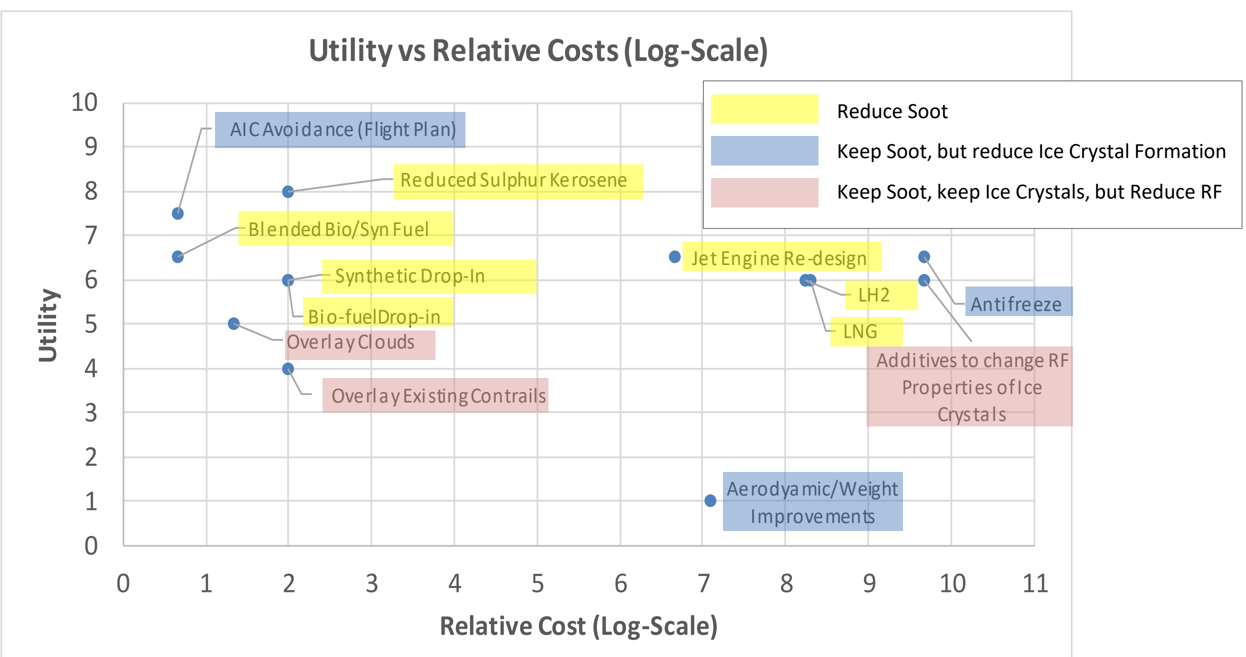

FIGURE 4: Utility vs Log-scale Relative Development plus Deployment Costs for each option

6 CONCLUSIONS

This paper provides an overview of Aircraft Induced Clouds (AIC) and their impact on Radiative Forcing (RF) contributing to global warming. The paper describes the “physics” of the formation and spreading of contrails and uses this as the basis for mitigation strategies. Critical parameters are the soot count in the jet engine emissions, the atmospheric conditions in the flight path for generating AIC, and the RF properties of the AIC.

The mitigation strategies can differentiated by the need for the airline fleet renewal. Low-cost, near-term mitigations include operational changes to the trajectory of the aircraft and adaptation of jet engine fuels. Whereas significant investment in production capacity is required to make bio and synthetic fuels feasible, AIC avoidance has low costs and barriers to implementation. Modifications to jet engines and alternate fuel sources (e.g. LH2 and LNG) would require fleet renewal, are expensive, and would take several decades.

Any mitigation efforts must consider the degree of uncertainty in the current scientific estimates of the AIC impact on RF, and the RF impact on the Earth’s temperature structure.

6.1 Uncertainty in Global Warming Impact from AIC

The impact of AIC on RF cannot be directly measured. The RF effects of AIC have to be estimated based on RF models and data on the properties and presence of AIC. The RF models and the methods for estimating AIC coverage exhibit varying degrees of uncertainty. The level of scientific understanding of AIC RF is considered low with an uncertainty range conservatively estimated to be on the order of 60% [4], [8]. Regional cirrus trends were used as a basis to compute a global mean RF value for AIC in 2000 of +0.030 W m–2 with a range of +0.01 to +0.08 W m–2 [41]. This value is not considered a best estimate because of the uncertainty in the optical properties of AIC and in the assumptions used to derive AIC cover. However, this value is in good agreement with the upper limit estimate for AIC RF in 1992 of +0.026 W m–2 derived from surface and satellite cloudiness observations [34]. A value of +0.03 W m–2 is close to the upper-limit estimate of +0.04 W m–2 derived for non-contrail cloudiness in IPCC-1999.

The current best estimate for the RF of persistent linear contrails for aircraft operations in 2000 is +0.010 W m–2 [42]. The value is based on independent estimates derived from [19] that were updated for increased aircraft traffic in [42] to give RF estimates of +0.015 W m–2 and +0.006 W m–2, respectively. The new estimates include diurnal changes in the solar RF, which decreases the net RF for a given contrail cover by about 20% [43].

There are also unexplained regional differences in contrail optical depths between Europe and the USA that have not been fully accounted for in model calculations [e.g. 36]. The global RF values for contrail and induced cloudiness are assumed to be proportional with distance flown by the global fleet if flight ambient conditions remain unchanged. However, individual persistent contrails are routinely observed to shear and spread, covering large additional areas with cirrus cloud [35]. Because spreading contrails lose their characteristic linear shape, a component of AIC is indistinguishable from background cirrus. Estimates of the ratio of induced cloudiness cover to that of persistent linear contrails range from 1.8 to 10 indicating the uncertainty in estimating AIC amounts [34], [40].

Initial attempts to quantify AIC used trend differences in cirrus cloudiness between regions of high and low aviation fuel consumption [4]. Since IPCC-1999, two studies have also found significant positive trends in cirrus cloudiness in some regions of high air traffic and found lower to negative trends outside air traffic regions [41]. Using the International Satellite Cloud Climatology Project (ISCCP) database, these studies derived cirrus cover trends for Europe of 1 to 2% per decade over the last two decades. A study with the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) provides further support for these trends [37]. However, cirrus trends that occurred due to natural variability, climate change or other anthropogenic effects could not be accounted for in these studies.

Persistent contrail cover has been calculated globally from meteorological data (e.g. [38]) or by using a modified cirrus cloud parametrization in a GCM [39].

Also, future changes in atmospheric humidity and temperature distributions in the upper troposphere will have consequences for AIC.

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AUTHORS CONTRIBUTION

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