JOURNAL OF AIRCRAFT
Vol. 44, No. 5, September–October 2007

Overview on Contrail and Cirrus Cloud Avoidance Technology

F. Noppel* and R. Singh†
Cranfield University, Bedfordshire, MK43 0AL England, United Kingdom

DOI: 10.2514/1.28655

Greenhouse gas emissions, contrails, and aviation-induced cirrus clouds are the principal pollutants from air traffic, which contribute to the anthropogenic global warming. Recent climate assessments have stressed the importance of contrails and aviation-induced cirrus clouds because they may contribute more than all other aircraft emissions combined. This paper reviews the mechanisms of contrail and aviation-induced cirrus cloud formation from which avoidance strategies are derived and discussed.

I. Introduction

RECENT climate assessments have stressed the importance of anthropogenic perturbations in the Earth's radiation budget. They ultimately lead to global warming, which has an impact on the socioeconomic development paths with unpredictable consequences in all respects. The perturbations are quantified by applying the principle of radiative forcing (RF), where the expected steady-state response in terms of global mean surface temperature is related linearly to the RF of a certain pollutant [1]

$$\Delta T_s = \lambda \mathrm{RF} \tag{1}$$

where λ is the climate sensitivity parameter.

Aviation-induced pollutants have been identified and assessed in terms of RF by the Intergovernmental Panel on Climate Change (IPCC) in 1999 [2]. Persistent contrails and aviation-induced cirrus clouds were recognized to contribute significantly to the overall aviation-induced RF. A more recent study suggests that approximately 20% of the total aviation-induced RF can be atrributed to linear persistent contrails [3], which is less than originally estimated by the IPCC. Annually and globally averaged global contrail cover and the associated RF are expected to nearly quadruple during the next decades as a result of an increase in air traffic [4].

Contrail cirrus clouds evolve from spreading persistent contrails and can cover large areas [5]. Studies suggest the area covered by contrail cirrus to be 10 times the area covered by linear persistent contrails [6]. Secondary cirrus form due to locally increased atmospheric aircraft soot and aerosol concentrations which would not form in the absence of air traffic [7–9]. Additionally, an indirect RF of aircraft induced particles is possible by modifying natural cirrus clouds [10]. Although the estimate of the RF from contrail cirrus, secondary cirrus, and cirrus cloud modification is uncertain at the current level of understanding, there is the potential that it exceeds the RF of all other emissions from air traffic combined [3].

Concerns regarding the environmental impact from persistent contrails, contrail cirrus, secondary cirrus, and cirrus cloud modification (PCC) have initiated the search for methods and technologies to avoid their formation. The mechanisms involved in the formation of PCC are multidisciplinary and make this a challenging task. They range over aircraft emissions, plume chemistry, aircraft wake dynamics, ice microphysics and radiative properties, the state of the atmosphere within the flight corridors, atmospheric dispersion rates, and engine technology. The next section reviews key processes involved in the formation of PCC from which abatement strategies are deduced and presented subsequently.

II. Review

Contrails are elongated clouds composed of ice crystals which form behind an aircraft when the wake becomes supersaturated with respect to water. Supersaturation can occur in the engine exhaust due to local variations in temperature and humidity. Alternatively, supersaturation can occur in the vicinity of lifting surfaces due to pressure disturbances or in the upwelling parts of the aircraft wake.

A. Engine-Provoked Contrails

The mechanisms for contrail formation provoked by the engines of an aircraft are generally well understood [11,12]. The exhaust jet of a jet engine is hotter and contains more water than the ambient air entering the engine. Additional water in the exhaust plume emerges due to the combustion of fossil fuel in the combustion chamber. The increase in temperature occurs due to restricted ability of jet engines to transform fuel-bound energy into useful work defined by the laws of thermodynamics [13]. Water condenses if the water partial pressure in the plume exceeds liquid supersaturation as the warm and humid exhaust mixes with the colder and less moist ambient air. The condensation of water occurs on particles such as soot and aerosols. Temperature, humidity, and mixing ratios in the plume are not necessarily uniformly distributed and the jet interaction with the aircraft wake has an influence on the mixing process. Generally, freezing is followed shortly after condensation as the relative humidity and the temperature drop in the diluting plume is resulting in local ice supersaturation. The ice particles evaporate if the ambient air is not supersaturated with respect to ice and the contrail disappears after a short time period. A short living contrail is known as a threshold contrail. Threshold contrails are not considered to be environmentally harming. A contrail persists in the case of ambient ice supersaturation and lasts as long as the surrounding air stays sufficiently ice supersaturated. Local atmospheric conditions provoke its evolution from a linear contrail to a contrail cirrus.

If the mixing of exhaust with the ambient air along a streamline within the plume is assumed to be adiabatic and isobaric with heat and water mixing at equal rates, it can be represented as a straight line in a water phase diagram, called the mixing line. The conditions for contrail formation are fulfilled if the mixing line crosses the area for which water is present in the liquid phase. The pressure at which mixing takes place is considered to be ambient pressure. The temperature exhaust is considered to be the stagnation temperature of the jet relative to the atmosphere frame of reference [14,15]. Based on the above assumptions, the slope G of the mixing line on a phase diagram is given by

Received 1 November 2006; revision received 29 January 2007; accepted for publication 3 February 2007.

*Ph.D. Student, School of Engineering, Department of Power and Propulsion; f.g.noppel@cranfield.ac.uk (Corresponding Author).
†Professor, School of Engineering, Department of Power and Propulsion.

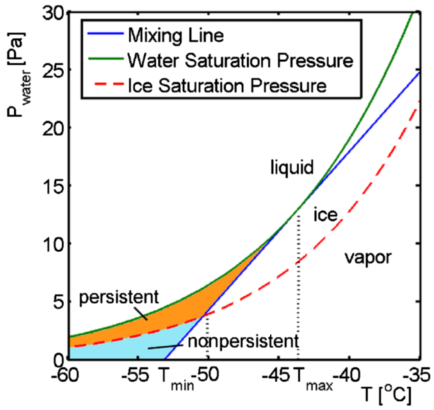

Fig. 1 Critical contrail formation temperatures. Polynomial fits to saturation pressure adopted from [17].

$$G = \frac{c_p EI_{H_2O} p_a}{q_{net}(1 - \eta_0)\omega} \tag{2}$$

where c_p is the specific heat capacity of air, EI_{H_2O} is the emission index for water, p_a is the atmospheric pressure, q_{net} is the fuel net calorific value, η_0 is the overall engine efficiency, and ω is the molar mass ratio of air to water [12]. The probability for contrail formation increases for higher values of G as the mixing line is more likely to cross the water vapor saturation pressure line. Hence higher engine efficiencies increase the potential for contrail formation.

Ice particles form only from the liquid phase [16]. A contrail would not form in an ice-supersaturated atmosphere if liquid supersaturation did not occur in the plume.

The critical mixing line defining the critical formation temperatures is a tangent to the water vapor pressure line in a water phase diagram as shown in Fig. 1. It originates from a point defining the state of the water contained in the exhaust of a jet engine. Because the exhaust temperature is a few hundred Kelvin higher than the ambient temperature, this point would lie far outside of Fig. 1. The formation of a persistent contrail occurs if the ambient conditions can be represented by a point inside the area labeled "persistent" in Fig. 1 as the resulting mixing line would cross the water saturation pressure line. A threshold contrail would occur if the ambient conditions can be represented by a point inside the area labeled "nonpersistent."

B. Plume Chemistry

Soot is naturally hydrophobic and requires high levels of supersaturation to provide effective condensation nuclei [18,19]. However, the supersaturation required for heterogeneous water nucleation on exhaust soot in the young plume is reduced due to its specific microporous structure and surface heterogeneity [20], and the presence of sulphuric acid. Sulphuric acid enhances the ability of soot particles to act as condensation nuclei. It results from the oxidation of fuel-bound sulfur and subsequent reaction with hydroxy radicals within the engine or in the jet regime of the plume [21]. Acid coatings form on soot particles via binary heterogeneous nucleation (condensation on a surface of two distinct types of substances) of sulphuric acid and water, or from collision with droplets consisting of water and sulphuric acid which emerged previously via binary homogeneous nucleation (formation of droplets by condensation of two distinct types of substances) [22]. Coagulated droplets consisting of water and sulphuric acid, referred to as aerosols, can also serve as condensation nuclei. Ice particles grow through water deposition or particle collision in the aging plume.

Contrail particle number density increases downstream of the plume because homogeneous nucleation requires longer time scales than heterogeneous nucleation [23]. A lower sulfur content leads to predominantly heterogeneous nucleation and prevents the formation of volatile particles. High fuel sulfur content leads to more volatile particles [24] whereas the number of volatile particles in the exhaust plume increases overproportionally with increasing fuel sulfur content [25]. It has been observed that a high fuel sulfur content causes a slight increase in the contrail formation temperatures.

C. Aircraft Wake Dynamics

The flow structure within aircraft wakes has an effect on the formation, dispersion, and persistence of contrails. In cruise conditions, two counter-rotating wing tip vortices are predominant in the aircraft wake. The evolution of the wake/vortex interaction is categorized into three sequential regimes [26,27]: 1) the jet regime which is equivalent to that of usual coflowing jets; 2) the deflection regime which corresponds to the entrainment and capture of the jet by the vortices; and 3) the shearing regime during which the plume is affected by convection and shearing processes generated by the rotational component of the velocity inside the vortex cores.

Recent studies suggest that cooling and vapor condensation are enhanced by the entrainment of the exhaust jet by the wing tip trailing vortices [28,29] and that plume dynamics have a significant effect on the contrail dispersion and particle size and number density [30]. A wake vortex pair descends due to the mutual induction of its circulation fields. Buoyancy forces increase due to adiabatic compression during vortex descent and diminish the descent rates over time [31]. Heating due to adiabatic compression of a falling vortex system can lead to significant ice crystal number depletion [32] depending on the ambient ice supersaturation, ice crystal number density, and wake characteristics.

D. Contrail Radiative Properties

The RF of PCC results from the interaction of the solar and the Earth's outgoing infrared radiation with their ice crystals. The RF becomes positive if the outgoing energy flux is reflected to a larger extend than the incoming energy flux. Sensitivity analysis shows that contrails predominantly cause a net heating effect [33]. Cooling is possible where contrails form over very cold surfaces with low ground albedo or over a very humid but cloud-free troposphere. It also occurs in contrails with very small ice particles and contrails containing particles with a small asymmetry factor. The RF of contrails grows with optical depth (the net forcing becomes negative for ice clouds with very large optical depth larger than that of contrails) and with increasing contrail cover. Warm and bright surfaces facilitate higher heating rates. Contrails with smaller particles cause a greater heating effect down to a certain particle size, below which the effect is reversed. Because solar flux is changing during the day at a given location on the globe, the RF varies with a maximum RF occurring during the night [34].

E. Ice-Supersaturated Regions

Ice-supersaturated regions in the atmosphere exist where the ambient humidity is insufficient for cirrus cloud formation [35]. Contrails can form and persist at supersaturation levels too low for natural cirrus cloud formation because temporarily large supersaturation in the aircraft wake allows nucleation. Because engine-provoked contrails form behind an aircraft only from the liquid phase [16], ambient ice supersaturation does not necessarily result in the formation of a contrail. However, the question is currently left unanswered when an aerodynamic contrail would form instead.

The occurrence of ice-supersaturated regions is altitude dependent [36] and varies seasonally [34]. On average, commercial airliners flying in the troposphere encounter ice supersaturation during 13.5% of their journey. For stratospheric flight the portion is only 2%. The vertical extent of ice-supersaturated regions is relatively small compared to their horizontal extension. If aircraft encountering ice supersaturation changed cruise altitude by less than 1000 m toward the nearest ice-subsaturated altitude, 99% of ice supersaturation could be avoided [37].

F. Aerodynamic Contrails

Pressure disturbances around the lifting surfaces and turbulence in the aircraft wake can initiate condensation. In case of ambient ice supersaturation, this will cause a persistent linear contrail with similar radiative properties as engine induced contrails [38]. Simulations suggest that adiabatic cooling can occur within the complex flowfield of an aircraft wake, which can trigger homogeneous freezing nucleation. Although the phenomenon of aerodynamic contrails is known, they have drawn only little attention from the scientific community. Possible environmentally related implications are not considered in global studies up to now.

G. Contrail Cirrus

Contrail cirrus may form from persistent contrails when aging aircraft exhaust particles provide nuclei susceptible to ice crystal formation [39] in a sufficiently high ice-supersaturated atmosphere. Contrails forming in a low ice-supersaturated atmosphere would persist but remain limited in their horizontal extension with shorter lifetimes [16].

The horizontal spreading of contrails is generally dominated by the ambient vertical shear of the horizontal wind. An increase in the vertical extent of a contrail occurs through depositional growth of ice crystals causing precipitation of larger ice particles and vertical mixing driven by radiative heating. Large particle growth rates can be found especially near the contrail's edges because of higher levels of ice supersaturation [40].

Progressively aging contrails exhibit a continuous decrease of ice crystal concentration and increasing mean diameter. Because contrail cirrus coverage has a considerable time lag with respect to air traffic, their occurrence is shifted toward night hours where their RF is stronger [6].

H. Secondary Cirrus and Cirrus Modification

An increase of soot particle concentration by more than 30% has been observed in regions highly frequented by aircraft [41]. The locally increased soot concentrations facilitate the formation of secondary cirrus clouds which would not form in the absence of air traffic [8,42]. Ice particles formed on soot during the formation of threshold contrails might not completely evaporate under subsaturated conditions. The remaining layers of ice turn soot into more effective condensation nuclei [41].

Aircraft soot can modify natural cirrus clouds by causing a decrease in effective ice crystal diameter and an increase in ice crystal number density [10]. Cloud modification generally depends on the ice-forming ability of coated soot particles and takes place in regions where natural ice nuclei are less efficient than aircraft soot. The modifications have an effect on the cloud's microphysical properties, enhance its optical depth and geometry, and prolong the cloud's lifetime [33]. This can lead to an increase in the cloud's RF. Persistent contrails which form within regions of prevailing natural cirrus clouds may compete for available water which can also have an impact on the microphysical and radiative properties of the cloud.

III. Mitigation Strategies

A framework to assist in the identification of possible strategies to mitigate the RF due to PCC has been deduced from the review. It is subdivided into four levels of coherency: RF → PCC frequency and radiative properties → physical principles → technological and operational enablers. The RF can be directly linked to PCC frequency and radiative properties, whereas the principles determining PCC frequency or radiative properties can be attributed to one of the following identified categories:

Particles and aerosols: particles and aerosols provide condensation nuclei for PCC and activate hydrophobic particles. They affect the formation and the radiative properties of PCC.

Wake dynamics: near-field and far-field interaction of the engine exhaust with the aircraft wake facilitates the mixing of the exhaust with ambient air. The evolution and interaction of the wake with the atmosphere has an effect on the development of the contrail and transition into contrail cirrus. Wake dynamics influence the formation of aerodynamic contrails.

Contrail potential: the condensation of water occurs only in the case of liquid supersaturation within the plume. Condensation can be triggered by humidity, pressure, and temperature variations in the aircraft wake.

Air traffic distribution: the RF from PCC, ambient conditions facilitating contrail formation and contrail persistence depend on the temporal and spatial distribution of aircraft routes.

Operational and technological enablers provide an engineering tool to reduce the RF from PCC. They function according to at least one of the aforementioned principles and can be attributed to at least one of the following groups:

Engine architecture: includes all possible modifications to the propulsion device or novel and revolutionary concepts.

Flight path: modifications to the spatial and temporal characteristics of the flight path trajectory of a single aircraft, the air traffic for a region, or the air traffic on a global scale.

Fuel and combustion: the type of energy source used to power the propulsion device. Control of emissions due to the conversion of stored energy into any other form of energy required to obtain a propulsive force.

Airframe and engine integration: all modifications to current technology or novel concepts regarding the airframe and the engine integration method.

Supplementary devices: devices which prevent by any means the formation of contrails, contrail cirrus, or aviation-induced cirrus clouds.

Some technological and operational enablers are discussed in the following sections.

A. Engine Architecture

Both the thermal and propulsive efficiency have increased significantly since the first commercial jets. Because higher values of overall efficiency are ultimately desired to save fuel and reduce carbon dioxide emissions, higher values of overall efficiency can be expected for future engines. The theoretical limit of overall efficiency for conventional engine architecture is about 0.56. This assumes open rotor technology, ultimate component efficiencies, and stoichiometric turbine inlet temperature [43]. The higher overall engine efficiency would increase the potential for contrail formation significantly when compared to current engines [see Eq. (2)].

Higher bypass ratios or open rotor devices would cause a reduction in the relative mass flow through the engine core and a reduction in the jet exit velocity. This could have an effect on the plume dispersion rate and the development of the aircraft wake. Open rotor devices induce an additional vortex in the jet as long as no counter-rotating two spool arrangement or guide vanes are applied. The additional swirl in the exhaust might affect the aircraft wake development and consequently contrail formation. Remotely driven fans are discussed in the aeronautical community as a possible future propulsion concept where the exhaust of the power generating device and the jet of the propulsive device are separated. This would have an impact on the humidity/temperature ratio in the core exhaust, very likely yielding an increase in the contrail formation potential.

The formation of contrails could be avoided by reducing the water content in the exhaust gases of a jet engine. A temperature drop of the exhaust gases inside the engine would be necessary to facilitate water condensation. This could be, for example, achieved with heat exchangers. The water condensate could be stored either onboard the aircraft or released into the atmosphere in the liquid phase for precipitation. A novel engine concept is proposed in [44] which exhibits the potential for lower emissions without producing contrails. Hydrogen fuel cells also represent an attractive application for this method [45].

Another novel engine concept discussed in the open domain is distributed propulsion [46,47] in the form of minigas turbines or remotely driven fans. Minigas turbines have the potential to reduce block fuel consumption but might operate with a lower overall efficiency compared to current designs [48]. The decrease in the overall efficiency would cause a reduction in the potential for contrail formation. Smaller plume diameters might lead to a smaller vertical band of the contrail thus reducing the chance for contrail cirrus formation. A distributed exhaust along the lifting body would also have an effect on the jet entrainment.

B. Airframe and Engine Integration

Aircraft geometry has an effect on the vortex structure and intensity. The relative position of the jet exhaust to the vortices determines its entrainment. The formation, evolution, and radiative properties of a contrail are affected in two ways [30]: 1) a more effective jet entrainment causes ice particle evaporation due to vortex descent and the associated adiabatic heating, and 2) less effective jet entrainment prevents vertical spreading of the contrail, reducing the chance for contrail cirrus formation and leading to less effective mixing of the exhaust gas with the ambient air. Configurations with a larger gap between exhaust and wing tip vortices (e.g., fuselage mounted engines) might reduce the probability of contrail dispersion and thus contrail cirrus. A more effective jet entrainment could be achieved by placing the jet closer to the vortices. Vortex intensity could be controlled via vortex generators, harmonic excitation by flaps, or an artificially induced swirl in the engine jet.

Some novel airframe concepts often discussed in the aeronautical community are the blended wing body and the joined wing aircraft. Both concepts potentially affect the vortex pattern and strength which might have an effect on contrail formation and persistence.

Studies suggest that the formation of aerodynamic contrails is possibly more likely to occur for heavy, slow, wide-body aircraft [38].

C. Flight Path

Contrail occurrences could be reduced by preventing aircraft from flying through regions in the atmosphere which facilitate the formation of persistent contrails. Regions susceptible to the formation of contrail cirrus have different characteristics and can be avoided independently. Three distinct approaches exist to mitigate the formation of contrails by changing cruise altitude: 1) change cruise altitude on a global scale [49]; 2) restrict cruise altitudes based upon atmospheric conditions for certain regions over a certain time period [50]; 3) change aircraft cruise altitude during flight depending on ambient conditions [37]. Ambient temperature, pressure, and humidity depend on altitude and differ geographically and seasonally. Simulations suggest that a downward displacement of the flight corridor on a global scale would result in a decrease in global contrail coverage especially during the winter months [49]. An increase in contrail cover would occur in regions with prevailing high altitude air traffic in the midlatitudes. The opposite would be true for an upward shift of the flight corridor. Aircraft optimized for lower altitudes might reduce the fuel burn penalty associated with the increase in drag. Because the stratosphere is much drier than the troposphere [36], stratospheric air traffic would reduce contrail cover considerably. However, there are concerns about ozone depletion due to the emission of nitrogen oxides of stratospheric air traffic. Simulations for air traffic over Europe suggest that approach 2 leads to a significant decrease in contrail cover. However, the required minimum separation between aircraft could not then be maintained due to the reduced number of available flight levels [51]. Noland and Williams [52] state that this could be alleviated by redesigning air traffic sectors. Option 3 would reduce contrail occurrences with possibly a smaller fuel burn penalty compared to options 1 and 2 [53]. The fuel burn penalty could be reduced by adapting the wing for different altitudes during the flight, for example, by applying variable camber wings.

Geographical or temporal variations in air traffic would have an impact on the RF of PCC due to differential ground albedo and variations in solar radiation. Nighttime flights during winter are responsible for most of the contrail RF [34]. In view of this, shifting air traffic to the time periods where contrail RF is lowest could be a solution. PCC over regions with low ground albedo would reduce their RF [33]; hence restricting flights over such regions would reduce the RF. However, this is probably not practical due to the location of airports, the associated substantial increase in fuel burn, and journey time. Simulations suggest that an increase in air traffic density around sunrise and sunset would reduce the RF due to persistent linear contrails [54]. This might be in conflict with the fact that secondary cirrus from contrails formed during evening hours persist during night and cause a stronger RF [6]. Furthermore, air traffic concentrated in the morning and evening hours is impractical from an economical point of view and would lead to an overloading during these times.

D. Fuel and Combustion

The particle size, their microphysical properties, particle number density, and the presence of aerosols in the exhaust plume have an effect on the radiative properties of PCC. Changing the radiative properties of PCC could reduce the RF from PCC. Hence, it might be desirable to either control particle and aerosol properties or ban them from the exhaust. Engine emissions emerge during the combustion process and may be tackled either during the combustion process itself or postcombustion via exhaust cleanup by means of filter systems. As these approaches very likely have an effect on engine weight and performance, an increase in fuel burn is probably inevitable.

Fuel-bound sulfur acts as a lubricant, which is required to prevent mechanical abrasion within the engine. It could be substituted by a lubricating fuel supplement. However, replacing fuel-bound sulfur might have no or only very little impact on contrail formation [20].

The switch to hydrogen-fueled aircraft is being widely discussed in the aeronautical community as their emissions are restricted to water and oxides of nitrogen only. Water emissions of these aircraft would be much higher. The emission index of water is 3.21 mass units of water per mass unit of liquid hydrogen as opposed to 1.26 mass units of water per mass unit of kerosene. Thus, the probability of contrail formation increases with the switch to hydrogen-fueled aircraft. Young contrails from hydrogen-fueled aircraft would probably consist of fewer but larger particles with a very high sensitivity to variations in background aerosols [55]. This would have an effect on the optical thickness and particle precipitation rate and hence on the associated RF of contrails from hydrogen-fueled aircraft. The switch to hydrogen-fueled aircraft would not have a significant effect on contrail formation frequency at high altitudes [56]. At lower altitudes, the air might be too warm to facilitate the formation of contrails from kerosene-fueled aircraft but not the formation of contrails from hydrogen-fueled aircraft. Studies suggest that the global annual mean contrail cover from hydrogen-fueled aircraft would increase by a factor of 1.56 compared to kerosene-fueled aircraft. However, the RF due to persistent contrails caused by a fleet of hydrogen-fueled aircraft could potentially be lower than the RF from contrails caused by a kerosene-fueled fleet. This is because the microphysical properties of contrail particles from hydrogen-fueled aircraft differ from the kerosene equivalents [57].

E. Supplementary Devices

Chemical treatment of the exhaust could potentially decrease the diameter of contrail ice particles [58]. The RF of contrails with very small particles might be negative. Alternatively, additions to the plume could be used to alter the saturation pressure of water [59]. Both methods require additional equipment and the chemicals to be transported during the journey which implies a weight and hence a fuel burn penalty. Additionally, the environmental impact of chemicals could quell its potential in commercial applications.

Ice crystal microphysical properties, the suppression of water vapor condensation, and evaporation of ice crystals could be achieved by applying electromagnetic radiation or sonochemical principles. However, both methods are currently unexplored.

IV. Discussion

At the current level of understanding, PCC mitigation strategies with respect to current aircraft and engine technology imply a fuel burn penalty. This will inevitably cause an increase in greenhouse

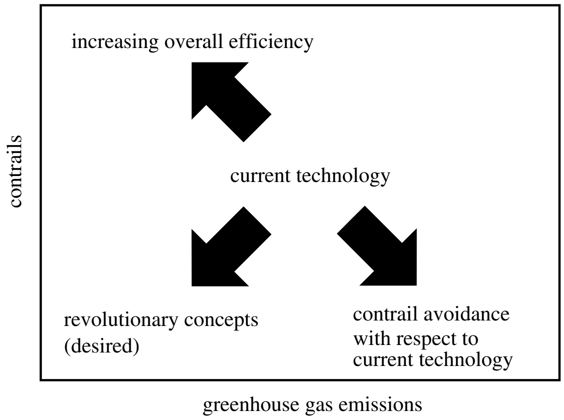

Fig. 2 Contrail avoidance with respect to current aircraft and engine technology.

gas emissions. A qualitative representation of this trend is given by the bottom right arrow in Fig. 2. Current technology trends indicate that next generation aircraft will be derivatives of present technology. Improvements in fuel economy will be mainly achieved through design advances on a system level to achieve reductions in weight and improvements in aerodynamics and engine efficiency. However, engines operating at higher efficiency are more likely to cause the formation of contrails. This trend is represented by the upper left arrow in Fig. 2. Ultimately, the long term goal is to reduce the RF from all aircraft pollutants simultaneously as indicated by the bottom left arrow in Fig. 2.

Current aircraft technology evolved from the requirements set by the economy within the framework of regulations regarding safety and environmental impact. Up to now, there is no considerable economical driving force for airlines or aircraft and engine manufacturers to reduce the environmental impact from PCC which would substitute the necessity of policies. However, it might not be justified to enforce PCC avoidance in the near future even though the RF caused by PCC might exceed the RF from all other (accumulated) aircraft pollutants. As the pollutants' lifetimes and feedback mechanisms differ from each other, so too do their long term impacts on the climate and socioeconomic development paths. RF is only a metric for the strength of a pollutant's perturbation in the planetary radiation budget. It cannot be used to assess the climatic or socioeconomical impacts. This becomes clear if the impact of climatically relevant emissions is regarded as a chain [60]: emissions $\rightarrow$ radiative forcing $\rightarrow$ climate impact $\rightarrow$ societal and ecosystem impact. It would be desirable to develop and introduce a metric that compares an impact that is more relevant than RF. Although the relevance of the impacts increases further down the chain, there is a corresponding increase in uncertainty and complexity in computational techniques.

There are indications to abandon PCC mitigation in the short term, but favor them in the long term such as the following:

1) It has been shown that the efficacy (the ratio of the climate sensitivity parameter for a given forcing agent relative to the response produced by a standard carbon dioxide forcing from the same initial climate state [61]) of contrails is smaller than 1.

2) Simulations suggest that the transient climate response of PCC is delayed compared to carbon dioxide [62].

3) Carbon dioxide remains in the atmosphere over a time period in the range of 100 years which is much larger than that of PCC in the range of minutes up to some hours.

Unlike carbon dioxide emissions, the RF from PCC would virtually become zero in the moment they are banned. The accumulated impact from PCC by the time they are avoided is potentially marginal compared to the overall impact of the long-lived carbon dioxide emissions. As a result, it might be desirable to only introduce PCC avoiding strategies if they virtually do not cause additional carbon dioxide emissions. As long as this is not the case, the overall long term impacts from aviation beyond RF could be far less severe if PCC avoidance was introduced in the more distant future when the associated fuel burn penalty is less significant. Hence, it might currently be more desirable to concentrate on more fuel efficient technologies along with further reductions in NO_x and noise. The long term goal should be the development of technologies which exhibit the potential to reduce carbon dioxide emissions along with PCC mitigation.

Possible PCC mitigating strategies outlined in previous sections exhibit fundamental differences in their physical and technical nature and can be combined to achieve the desired effect. The challenge is to accommodate the forecast growth in air traffic of 5% p.a. (per annum) during the next decades [63] while reducing the environmental impact from air traffic by selecting a strategy or a combination of strategies which yield the best compromise between conflicting objectives such as safety, economic efficiency, affordability, reliability, accessibility, risk, and environmental impact.

References

[1] Hansen, J., Sato, M., and Ruedy, R., "Radiative Forcing Climate Response," *Journal of Geophysical Research*, Vol. 102, No. D6, March 1997, pp. 6831–6864.

[2] Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J., and McFarland, M. (eds.), *Aviation and the Global Atmosphere*, A Special Report of IPCC Working Groups I and III, Cambridge University Press, Cambridge, U.K., 1999.

[3] Sausen, R., Isaksen, I., Grewe, V., Hauglustaine, D., Lee, D., Gunnar, M., Köhler, M. O., Pitari, G., Schumann, U., Stordal, F., and Zerefos, C., "Aviation Radiative Forcing in 2000: An Update on IPCC (1999)," *Meteorologische Zeitschrift;Acta Scientiarium Naturalium Universitatis Normalis Hunanensis*, Vol. 14, No. 4, Aug. 2005, pp. 555–561.

[4] Marquart, S., Ponater, M., Mager, F., and Sausen, R., "Future Development of Contrail Cover, Optical Depth, and Radiative Forcing: Impacts of Increasing Air Traffic and Climate Change," *Journal of Climate*, Vol. 16, Sept. 2003, pp. 2890–2904.

[5] Minnis, P., Young, D. F., Garber, D. P., Nguyen, L., Smith, W. L., and Palikonda, R., "Transformation of Contrails into Cirrus Euring SUCCESS," *Geophysical Research Letters*, Vol. 25, No. 8, 1998, pp. 1157–1160.

[6] Mannstein, H., and Schumann, U., "Aircraft Induced Cirrus Clouds over Europe," *Meteorologische Zeitschrift*, Vol. 14, No. 4, Aug. 2005, pp. 549–554.

[7] Zerefos, C. S., Eleftheratos, K., Balis, D. S., Zanis, P., Tselioudis, G., and Meleti, C., "Evidence of Impact of Aviation on Cirrus Cloud Formation," *Atmospheric Chemistry and Physics Discussions*, Vol. 3, June 2003, pp. 3335–3359.

[8] Stordal, F., Myhre, G., Arlander, W., Svendby, T., Stordal, E. J. G., Rossow, W. B., and Lee, D. S., "Is There a Trend in Cirrus Cloud Cover due to Aircraft Traffic?," *Atmospheric Chemistry and Physics Discussion*, Vol. 4, Oct. 2004, pp. 6473–6501.

[9] Jensen, E., and Toon, O. B., "The Potential Impact of Soot Particles from Aircraft Exhaust on Cirrus Clouds," *Geophysical Reserach Letters*, Vol. 24, No. 3, 1997, pp. 249–252.

[10] Kristensson, A., Gayet, J.-F., Ström, J., and Auriol, F., "In Situ Observations of Reduction in Effective Crystal Diameter in Cirrus Clouds Near Flight Corridors," *Geophysical Reserach Letters*, Vol. 27, No. 5, March 2000, pp. 681–684.

[11] Appelman, H., "The Formation of Exhaust Condensation Trails by Jet Aircraft," *Bulletin American Meteorological Society*, Vol. 34, No. 1, Jan. 1953, pp. 14–20.

[12] Schumann, U., "On Conditions for Contrail Formation from Aircraft Exhausts," *Meteorologische Zeitschrift*, Vol. 5, Feb. 1996, pp. 4–23.

[13] Saravanamuttoo, H. I. H., Rogers, G. F. C., and Cohen, H., *Gas Turbine Theory*, 5th ed., Prentice–Hall, Upper Saddle River, NJ, 2001.

[14] Schumann, U., "Influence of Propulsion Efficiency on Contrail Formation," *Aerospace Science and Technology*, Vol. 4, No. 6, 2000, pp. 391–401.

[15] Schumann, U., Busen, R., and Plohr, M., "Experimental Test of the Influence of Propulsion Efficiency on Contrail Formation," *Journal of Aircraft*, Vol. 37, No. 6, 2000, pp. 1083–1087.

[16] Jensen, E. J., Toon, O. B., Kinne, S. K., Sachse, G. W., Anderson, B. E., Chan, K. R., Twohy, C. H., Gandrud, B., Heymsfield, A., and Miake-Lye, C., "Environmental Conditions Required for Contrail Formation and Persistence," *Journal of Geophysical Research*, Vol. 103, No. D4, Feb. 1998, pp. 3929–3936.

[17] Flatau, P. J., Walko, R. L., and Cotton, W. R., "Polynomial Fits to Saturation Pressure," *Journal of Applied Meteorology*, Vol. 31, No. 12,

Dec. 1992, pp. 1507–1513.
[18] Wyslouzil, B. E., Carleton, K. L., Sonnenfroh, D. M., Rawlins, W. T., and Arnold, S., "Observation of Hydration of Single, Modified Carbon Aerosols," *Geophysical Research Letters*, Vol. 21, No. 19, Sept. 1994, pp. 2107–2110.
[19] Kärcher, B., Peter, T., Biermann, U. N., and Schumann, U., "The Initial Composition of Jet Condensation Trails," *Journal of the Atmosphere Sciences*, Vol. 53, No. 21, 1996, pp. 3066–3083.
[20] Popovitcheva, O. B., Trukhin, M. E., Persiantseva, N. M., and Shonija, N. K., "Water Adsorption on Aircraft-Combustor Soot Under Young Plume Conditions," *Atmospheric Environment*, Vol. 35, No. 9, 2001, pp. 1673–1676.
[21] Starik, A. M., Savelév, A. M., Titova, N. S., and Schumann, U., "Modeling of Sulfur Gases and Chemiions in Aircraft Engines," *Aerospace, Science and Technology*, Vol. 6, No. 1, 2002, pp. 63–81.
[22] Kärcher, B., "Aviation-Produced Aerosols and Contrails," *Surveys in Geophysics*, Vol. 20, No. 2, 1999, pp. 113–167.
[23] Gierens, K., "On the Transition Between Heterogeneous and Homogeneous Freezing," *Atmospheric Chemistry Physics*, Vol. 3, No. 2, April 2003, pp. 437–446.
[24] Petzold, A., Busen, R., Schröder, F. P., Baumann, R., Kuhn, M., Ström, J., Hagen, D. E., Whitefield, P. D., Baumgardner, D., Arnold, F., Borrmann, S., and Schumann, U., "Near-Field Measurements on Contrail Properties from Fuels with Different Sulfur Content," *Journal of Geophysical Research*, Vol. 102, No. D25, Dec. 1997, pp. 29867–29880.
[25] Schumann, U., Ström, J., Busen, R., Baumann, R., Gierens, K., Krautstrunk, M., Schröder, F. P., and Stingl, J., "In Situ Observations of Particles in Jet Aircraft Exhausts and Contrail for Different Sulfur-Containing Fuels," *Journal of Geophysical Research*, Vol. 101, No. D3, March 1996, pp. 6853–6869.
[26] Jacquin, L., and Garnier, F., "On the Dynamics of Engine Jets Behind a Transport Aircraft," AGARD FDP Symposium, CP-584, May 1996.
[27] Brunet, S., Garnier, F., and Jacquin, L., "Numerical/Experimental Simulation of Exhaust Jet Mixing in Wake Vortex," AIAA Paper 99-3418, 1999.
[28] Paoli, R., Helie, J., and Poinsot, T., "Contrail Formation in Aircraft Wakes," *Journal of Fluid Mechanics*, Vol. 502, March 2004, pp. 361–373.
[29] Paoli, R., and Garnier, F., "Interaction of Exhaust Jets and Aircraft Wake Vortices: Smallscale Dynamics and Potential Microphysical-chemical Transformations," *Comptes Rendus Physique*, Vol. 6, No. 4–5, 2005, pp. 525–547.
[30] Lewellen, D. C., and Lewellen, W. S., "The Effects of Aircraft Wake Dynamics on Contrail Development," *Journal of the Atmospheric Sciences*, Vol. 58, Feb. 2001, pp. 390–406.
[31] Proctor, F. H., Hinton, D. A., Han, J., Schowalter, D. G., and Lin, Y.-L., "Two Dimensional Wake Vortex Simulations in the Atmosphere: Preliminary Sensitivity Studies," Tech. Rept. NASA-AIAA-97-0056, 1997.
[32] Gierens, K., and Jensen, E., "A Numerical Study of the Contrail-to-Cirrus Transition," *Geophysical Research Letters*, Vol. 25, No. 23, Dec. 1998, pp. 4341–4344.
[33] Meerkötter, R., Schumann, U., Doelling, R. D., Minnis, O., Takajima, T., and Tsushima, Y., "Radiative Forcing by Contrails," *Annales Geophysicae*, Vol. 17, No. 8, Aug. 1999, pp. 1080–1094.
[34] Stuber, N., Forster, O., Rädel, G., and Shine, K., "The Importance of the Diurnal and Annual Cycle of Air Traffic for Contrail Radiative Forcing," *Nature (London)*, Vol. 441, No. 15, 2006, pp. 864–867.
[35] Heymsfield, A. J., Miloshevich, L. M., and Twohy, C., "Upper-Tropospheric Relative Humidity Observations and Implications for Cirrus Ice Nucleation," *Geophysical Research Letters*, Vol. 25, No. 9, May 1998, pp. 1343–1346.
[36] Gierens, K., Schumann, U., Helten, M., Schmit, H., and Marenco, A., "A Distribution Law for Relative Humidity in the Upper Troposphere and Lower Stratosphere Derived from Three Years of MOZAIC Measurements," *Annales Geophysicae*, Vol. 17, No. 9, 1999, pp. 1218–1226.
[37] Mannstein, H., Spichtinger, P., and Gierens, K., "A Note on How to Avoid Contrail Cirrus," *Transportation Research Part D: Transport and Environment*, Vol. 5, No. 10, Sept. 2005, pp. 421–426.
[38] Gierens, K. M., and Ström, J., "A Numerical Study of Aircraft Wake Induced Ice Cloud Formation," *Journal of Atmospheric Sciences*, Vol. 55, No. 21, Nov. 1998, pp. 3253–3263.
[39] Schröder, F., Kärcher, B., Duroure, C., Ström, J., Petzold, A., Gayet, J.-F., Strauss, B., Wendling, P., and Borrmann, S., "On the Transition of Contrails into Cirrus Clouds," *Journal of the Atmospheric Sciences*, Vol. 57, No. 4, 2000, pp. 464–480.
[40] Jensen, E. J., Ackerman, A. S., Stevens, D. E., Toon, O. B., and Minnis, P., "Spreading and Growth of Contrails in a Sheared Environment," *Journal of Geophysical Research*, Vol. 103, No. D24, Dec. 1998, pp. 31557–31567.
[41] Kärcher, B., and Lohmann, U., "A Parameterization of Cirrus Cloud Formation: Heterogeneous Freezing," *Journal of Geophysical Research*, Vol. 108, No. D14, 2003, AAC2-1.
[42] Zerefos, C. S., Eleftheratos, K., Balis, D. S., Zanis, P., Tselioudis, G., and Meleti, C., "Evidence of Impact of Aviation on Cirrus Cloud Formation," *Atmospheric Chemistry and Physics*, Vol. 3, Oct. 2003, pp. 1633–1644.
[43] Green, J. E., "Mitigating the Environmental Impact of Aviation: Opportunities and Priorities," *The Aeronautical Journal*, Vol. 109, No. 1099, Sept. 2005, pp. 361–416.
[44] Noppel, F., Singh, R., and Taylor, M., "Novel Engine Concept to Suppress Contrail and Cirrus Cloud Formation," *Proceedings of the International Conference on Transport, Climate and Atmosphere* (to be published).
[45] Alexander, D., Lee, Y.-M., Guynn, M., and Bushnell, D., "Emissionless Aircraft Study," AIAA Paper 2002-4056, July 2002.
[46] Sehra, K. A., and Whitlow, W., "Propulsion and Power for 21st Century Aviation," *Progress in Aerospace Sciences*, Vol. 40, May 2004, pp. 199–235.
[47] Campbell, D. J., "Revolutionary Propulsion and Power for 21st Century Aviation," AIAA Paper 2003-2561, July 2003.
[48] Ameyugo, G., Taylor, M., and Singh, R., "Distributed Propulsion Feasibility Studies," *Proceedings of the 25th International Congress of the Aeronautical Sciences*, Sept. 2006.
[49] Fichter, C., Marquart, S., Sausen, R., and Lee, D. S., "The Impact of Cruise Altitude on Contrails and Related Radiative Forcing," *Meteorologische Zeitschrift*, Vol. 14, No. 4, Aug. 2005, pp. 563–572.
[50] Williams, V., and Noland, R. B., "Variability of Contrail Formation Conditions and the Implications for Policies to Reduce the Climate Impacts of Aviation," *Transportation Research D*, Vol. 10, No. 4, 2005, pp. 169–280.
[51] Williams, V., and Noland, R. B., "Reducing the Climate Change Impacts of Aviation by Restricting Cruise Altitudes," *Transportation Research D*, Vol. 7, No. 6, 2002, pp. 451–464.
[52] Noland, R. B., and Williams, V., "Policies for Mitigating Contrail Formation from Aircraft," *Proceedings of the AAC-Conference*, AAC, Friedrichshafen, June 2003, pp. 328–333.
[53] Noppel, F., Singh, R., and Taylor, M., "Contrail and Cirrus Cloud Avoidance," *Proceedings of the 25th International Congress of the Aeronautical Sciences*, Sept. 2006.
[54] Myhre, G., and Stordal, F., "On the Tradeoff of the Solar and Thermal Infrared Radiative Impact of Contrails," *Geophysical Research Letters*, Vol. 28, No. 16, Aug. 2001, pp. 3119–3122.
[55] Ström, L., and Gierens, K., "First Simulations of Cryoplane Contrails," *Journal of Geophysical Research*, Vol. 107, No. D18, 2002, 2-1.
[56] Marquart, S., Sausen, R., Ponater, M., and Grewe, V., "Estimate of the Climate Impact of Cryoplanes," *Aerospace Science and Technology*, Vol. 5, No. 1, 2001, pp. 73–84.
[57] Marquart, S., Ponater, M., Ström, L., and Gierens, K., "An Upgrade Estimate of the Radiative Forcing of Cryoplane Contrails," *Meteorologische Zeitschrift*, Vol. 14, No. 4, Aug. 2005, pp. 573–582.
[58] Andreson, C. E., Birstein, S. J., and Silverman, B. A., "Method and Apparatus for Supressing Contrails," U.S. Patent No. 3,517,505, filed June 1970.
[59] Singh, S., "Method of Suppressing Formation of Contrails and Solution Therefor," U.S. Patent No. 5,005,355, filed April 1991.
[60] Shine, K. P., Fuglestvedt, J. S., Hailemariam, K., and Stuber, N., "Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases," *Climatic Change*, Vol. 68, No. 3, 2005, pp. 281–302.
[61] Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D., Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M., and Zhang, S., "Efficacy of Climate Forcings," *Journal of Geophysical Research*, Vol. 110, No. D18, Sept. 2005, D18104.
[62] Ponater, M., Marquart, S., Sausen, R., and Schumann, U., "On Contrail Climate Sensitivity," *Geophysical Research Letters*, Vol. 32, May 2005, 10706.
[63] Eyers, C. J., Norman, P., Middel, J., Plohr, M., Michot, S., Atkinson, K., and Christou, R. A., "AERO2k Global Aviation Emission Inventories for 2002 and 2025," EC, G4RDCT-2000-00382, April 2004.