Environmental Research Letters

LETTER

Impact of biofuels on contrail warming

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Keywords: contrails, aviation, climate, alternative fuels, contrail cirrus, biofuels

Supplementary material for this article is available online

Abstract

Contrails and contrail-cirrus may be the largest source of radiative forcing (RF) attributable to aviation. Biomass-derived alternative jet fuels are a potentially major way to mitigate the climate impacts of aviation by reducing lifecycle CO\textsubscript{2} emissions. Given the up to 90% reduction in soot emissions from paraffinic biofuels, the potential for a significant impact on contrail RF due to the reduction in contrail-forming ice nuclei (IN) remains an open question. We simulate contrail formation and evolution to quantify RF over the United States under different emissions scenarios. Replacing conventional jet fuels with paraffinic biofuels generates two competing effects. First, the higher water emissions index results in an increase in contrail occurrence (∼+8%). On the other hand, these contrails are composed of larger diameter crystals (∼+58%) at lower number concentrations (∼−75%), reducing both contrail optical depth (∼−29%) and albedo (∼−32%). The net changes in contrail RF induced by switching to biofuels range from −4% to +18% among a range of assumed ice crystal habits (shapes). In comparison, cleaner burning engines (with no increase in water emissions index) result in changes to net contrail RF ranging between −13% and +5% depending on habit. Thus, we find that even 67% to 75% reductions in aircraft soot emissions are insufficient to substantially reduce warming from contrails, and that the use of biofuels may either increase or decrease contrail warming—contrary to previous expectations of a significant decrease in warming.

1. Introduction

Condensation trails form in the wake of aircraft under certain meteorological conditions of temperature and humidity (Schumann 1996), predominantly through the formation of water droplets around particles emitted by aircraft, which serve as ice nuclei (IN) that lead to ice crystals predominantly through heterogeneous freezing. Aircraft-emitted IN are mainly nonvolatile particles, in particular soot (Kärcher and Yu 2009, Schumann 2012), although the role of volatile particles is uncertain especially in low soot conditions (Kärcher and Yu 2009), and homogeneous nucleation is potentially significant as well. In an ice-supersaturated atmosphere, contrails can last several hours, evolving into contrail cirrus indistinguishable from natural cirrus (Burkhardt and Kärcher 2011, Haywood et al 2009). Acting like high, thin ice clouds, contrails are more effective at trapping outgoing longwave radiation than at reflecting incoming shortwave radiation back to space (Burkhardt and Kärcher 2011, Hartmann et al 1992, IPCC 2013, Schumann and Graf 2013). As a result, contrails are estimated to be the largest radiative forcing (RF) component attributable to aviation (Burkhardt and Kärcher 2011, IPCC 2013). Biofuels have been identified as an opportunity to mitigate aviation’s climate impact by reducing fossil CO\textsubscript{2} emissions. Based on measurements of reduced soot emissions at cruise (Moore et al 2017) and model results showing reductions in contrail optical depth (Kärcher 2016), the potential of biofuels to reduce the climate impact of contrails has become an important question. Here, we conduct the first assessment of the effect of biofuels on contrail radiative forcing, as well as the related impact of reductions in soot emissions associated with improvements in combustor technology.
Table 1. Fuel properties and total, daytime and nighttime RF for all fuel/emissions configurations simulated by CERM over the US (57°W–140°W longitude and 16°N–58°N latitude). The range of RF values represent uncertainty dependent on the assumption of ice crystal habit. Percentages are reported for pairwise comparisons.

| Fuel properties | Radiative impact of contrails/contrail cirrus over the US domain |
|----------------|---------------------------------------------------------------|
|                | $E_{\text{H}_2\text{O}}$ | LHV | $E_{\text{IN}}$ | RF | $R_{\text{day}}$ | $R_{\text{night}}$ |
|                | [kg kg$^{-1}$]   | [MJ kg$^{-1}$] | [10$^{15}$ kg$^{-1}$] | [mW m$^{-2}$] | [mW m$^{-2}$] | [mW m$^{-2}$] |
| Conventional Fuel (Baseline) | 1.23 | 43.13 | 2.63 | 22 to 68 | −29 to 34 | 53 to 108 |
| Paraffinic Biofuel | 1.37 | 44.08 | 0.66 | 23 to 75 | −10 to 53 | 44 to 96 |
| Clean Burn | 1.23 | 43.13 | 0.90 | 21 to 67 | −12 to 45 | 42 to 89 |

$E_{\text{H}_2\text{O}}$ and LHV indicate the emission index of water vapor and the lower heating value of the two fuel types used, respectively. For all fuel cases, $E_{\text{H}_2\text{O}}$ is computed from stoichiometry, assuming complete combustion.

To this end, we developed the Contrail Evolution and Radiation Model (CERM) to simulate the main dynamical and microphysical processes occurring throughout a contrail’s lifetime to compute contrail RF.

CERM simulations of contrails and contrail cirrus are run for one year over the United States under a set of three scenarios with varying fuel types and emission indices of suitable ice nuclei ($E_{\text{IN}}$). In the first (baseline) scenario, the US aviation fleet utilizes conventional jet fuel with $E_{\text{IN}} = 2.63 \times 10^{15}$ kg$^{-1}$. This is consistent with recent estimates (Stettler et al. 2015), assuming most of the ice nucleation at contrail formation occurs around aviation-emitted black carbon (soot) (Kärcher and Yu 2009). We present our results in terms of IN emissions to separate our analysis from uncertainty associated with which specific particles constitute IN. In the second scenario, paraffinic biofuels are assumed to be used by the entire US fleet (and all over-flights). This scenario uses paraffinic biofuels (e.g. biomass-derived Fischer-Tropsch (FT) or hydrous processed esters and fatty acids (HEFA) fuels) with $E_{\text{IN}} = 0.66 \times 10^{15}$ kg$^{-1}$, a reduction of 75% (Speth et al. 2015) with respect to the baseline, and the (higher) stoichiometric water vapor emissions. This reduction is consistent with the results of Moore et al. (2017) who found 26%–48% reductions in the particle number emissions index for a 50% HEFA blend at cruise conditions. (We note that results from our paraffinic biofuel scenario are also applicable to other chemically similar fuels, e.g. coal-derived FT alternative jet fuel.) In the third and final scenario, we assess the potential impact of cleaner burning engines using conventional jet fuel, with $E_{\text{IN}} = 0.90 \times 10^{15}$ kg$^{-1}$ (Wilkerson et al. 2010), which is intended to demonstrate the effect of advances in combustor technology reducing soot emissions.

2. Methods

2.1. Model structure and input data

The Contrail Evolution and Radiation Model (CERM) developed for this study evaluates contrails and contrail cirrus characteristics and radiative impact over a full year, using a 1 hour time resolution and a 13.5 km horizontal grid resolution covering the contiguous United States (approximately 57°W–140°W longitude and 16°N–58°N latitude), with 10 equally spaced vertical pressure levels ranging from 400 to 150 hPa. CERM uses aircraft tracking and fuel burn data for 2006 taken from the Aviation Environmental Design Tool (AEDT) (Wilkerson et al. 2010). Meteorological fields are taken from the National Oceanic and Atmospheric Administration (NOAA) Rapid Refresh (RAP) dataset (National Oceanic and Atmospheric Administration Earth System Research Laboratory 2015). Data include temperature, three-dimensional wind speed fields and relative humidity with respect to liquid water. Contrail simulation results are highly dependent on the accuracy of the meteorological fields at flight altitudes. We find that the RAP dataset is locally ice-supersaturated approximately 12% of the time over an annual cycle at altitudes between 7 km and 13 km. This is lower than some other estimates in the literature with values closer to 15% (Gierens et al. 2012, Irvine and Shine 2015). However, the RAP dataset is specifically for North America while other results are global.

2.2. Contrail formation and initialization

Meteorology and flight data are used to compute contrail formation using the Schmidt–Applemann Criterion (SAC) (Schumann 1996), which is formulated in CERM following the method described in Ponater et al. (2002). Overall engine efficiency is set to 0.45, a value consistent with modern jet engine performance parameters (Cumpsty 2003), though this may be higher than the fleet average for 2006. Only persistent contrails are simulated in CERM; therefore the SAC is integrated with a persistence condition of ice-supersaturated background atmosphere, with ambient relative humidity with respect to ice computed from input meteorological data of temperature and relative humidity with respect to liquid water (Alduchov and Eskridge 1996, Murphy and Koop 2005). The initial number of ice crystals within each contrail is obtained from aircraft fuel burn data by applying the IN emission index corresponding to the specific fuel/emission scenario simulated (see table 1). Aircraft-emitted ice
nuclei responsible for contrail formation are treated in CERM as monodisperse with diameter of 40 nm (Petzold et al 2003), and bulk density of 1000 kg m$^{-3}$ (Durdina et al 2014). These characteristics are typical of aircraft-emitted soot particles, which are assumed to be contrail formation precursors following several models available in the literature (Burkhardt and Kärcher 2011, Kärcher et al 1998, Schumann 2012).

2.3. Contrail vortex phase modeling
After contrail formation is simulated, CERM models processes occurring at the early stages of contrail lifetime. Wake vortex downwash determines adiabatic heating of contrails, and a consequent ice crystal sublimation (Holzäpfel and Gerz 1999), which is modeled through a parameterization by Schumann (Schumann 2012). The parameterization utilizes a constant vortex sinking distance $\Delta z = 100$ meters, a value suggested both by empirical (Sussmann and Gierens 1999) and computational (Lewellen and Lewellen 2001) evidence. Contrail dilution and spreading in the vortex phase are modeled as described by Schumann (2012). CERM also accounts for entrainment of potential ice nuclei from the ambient atmosphere, a phenomenon consistent with cirrus ice residuals sampling campaigns (Cziczo and Froyd 2014, Twohy and Gandrud 1998). Given the high uncertainties in the type of particles serving as ice nuclei (Cziczo and Froyd 2014, Twohy and Gandrud 1998), no characterization is given about the nature of ice nuclei in the background atmosphere, and the concentrations are taken as uniformly distributed IN across the domain (well-mixed upper troposphere) (Hendricks et al 2004). Background ice nuclei in this study are assumed at the concentration of 2/L, following results from measurement campaigns (DeMott et al 2010, DeMott et al 2011). Entrainment of ice nuclei from the background atmosphere starts in the vortex phase and occurs at all stages of contrail lifetime, and affects the total number of ice crystals within aging contrails, the processes of ice crystal growth and of ambient water vapor uptake.

2.4. Dynamics, turbulent diffusion and wind shear
CERM simulates the advection and gravitational settling of contrails through a Lagrangian dynamics module. Contrail dynamical processes are assumed to occur simultaneously and uniformly across all the ice crystals (assumed spherical) (Li et al 2013), and are driven by the wind velocity fields throughout the domain (Schumann 2012) and by the gravitational fall speed of the ice crystals within the contrails (Seinfeld and Pandis 2016). Throughout their lifetime, contrails are modeled as Gaussian plumes with elliptical cross-sections by a parameterization of dilution, turbulent diffusion and wind shear (Schumann 2012). Atmospheric turbulence levels are assumed following Schumann (2012). At the hourly time resolution of the model, contrails evolve in the atmosphere and persist as long as they remain in ice-supersaturated regions.

2.5. Ice crystal growth
While they are advected and spread in the atmosphere, contrails entrain background air and incorporate new available ice nuclei (DeMott et al 2010, DeMott et al 2011). These fresh IN generate new ice crystals within the contrails, and induce further entrainment of ambient water offering a total larger surface for condensation of ice-supersaturated water vapor. Throughout their lifetime, ice crystals are simulated to grow in size by depositional uptake of background water vapor. This is modeled from Fick’s first and second laws, which regulate the diffusion of aerosol particles and predict a larger water uptake for a larger atmospheric supersaturation with respect to ice (Pruppacher and Klett 2010). The number of ice crystals within contrails changes as contrails age due to entrainment of ambient ice nuclei and to aggregation related to the mixing of contrail with ambient air and plume-internal turbulence (Schumann 2012).

2.6. Optical depth and radiative forcing
Optical depth at 550 nm at every stage of contrail lifetime is computed utilizing an approach developed by Schumann (2012), using Mie theory and taking the refractive index for ice to be 1.31. At each time step, ice crystal size, ice crystal number concentration, horizontal area cover, depth, ice water content and optical depth are computed for each of the simulated contrails. A parameterized radiative forcing model (Schumann et al 2012) is used to compute the radiative forcing from the modeled contrails and contrail cirrus over the United States of America. Planetary albedo, radiative fluxes and background cloud cover data necessary for the RF computations are obtained from the NASA CERES satellite inventory (NASA Langley Research Center Atmospheric Science Data Center 2015). The solar zenith angle is computed at each location according to the local time of day, as described in the supplementary material available at stacks.iop.org/ERL/12/114013/mmedia. Shortwave and longwave radiative forcing are therefore calculated with five ice crystal habit assumptions considered (spherical, solid hexagonal columns, hollow hexagonal columns, plates and droxtals) as modeled by Schumann et al (2012) that correspond to the range of RF values presented in this paper. Comparisons between cases are made pairwise assuming the same ice crystal habit in each case. The percentage changes in RF presented in table 1 follow this paired comparison approach, and further details broken down by ice crystal habit are shown in the supplementary material. For the purpose of presenting results, the daytime and nighttime RF components are separated by computing local sunrise and sunset throughout the computational domain (Kalogirou 2014) and average values are computed over these time periods. A detailed description of CERM’s structure and dynamics, microphysics, and radiation modules, together with comparisons of the results with existing literature is available in the supplementary material.
3. Results

Considering one-year contrail simulations in the conventional and paraffinic biofuel cases, we find that utilizing biofuels results in 8% more contrails over the United States. This is due to the 11% higher water emissions index of biofuels with respect to conventional jet fuel (see table 1). Higher water vapor emissions increase humidity within plumes, resulting in higher threshold temperatures below which contrails form after the passage of an aircraft (Schumann 1996). This enhances the likelihood of contrail occurrence. Contrails forming in the biofuel case are characterized by ice crystal number concentrations on average 75% lower than their counterparts in the conventional fuel case (see figure 1(a)). This reduction is due to the lower number of IN available for the formation of crystals in the early stages of contrail lifetime. The lower number of ice crystals reduces the competition for uptake of ambient water vapor above ice-saturation throughout contrail lifetime, yielding larger crystals (∼+58% in diameter with respect to the conventional fuel case; see figure 1(b)).

Changes in crystal concentration and size affect contrail optical properties (Schumann et al 2012), resulting in a lower average contrail optical depth (within regions where contrails are present) at 550 nm for contrails formed by biofuels, decreasing to ~0.020 from the average ~0.028 computed in the conventional fuel case (~29%). A reduction in contrail optical depth is expected to decrease the warming longwave RF to a larger extent than the cooling shortwave RF, thus generally yielding a lower net radiative forcing (Schumann et al 2012). Nevertheless, the cooling effect due to the reduction in optical depth for contrails formed in the biofuel case is counterbalanced by a lower contrail albedo, i.e. the extent to which these clouds scatter incoming solar radiation back to space. The annually-averaged planetary albedo change induced by contrails decreases from $1.18 \times 10^{-3}$ in the conventional fuel case to $8.03 \times 10^{-5}$ in the biofuel case (~32%). This albedo reduction is due to the larger ice crystals and lower ice number concentrations, i.e. a (reverse) Twomey effect (Twomey 1974). The Twomey effect is an increase in albedo for clouds ‘polluted’ by anthropogenic emissions, and thus composed of droplets in larger number and smaller sizes. The effect also occurs in contrails, since the solar albedo of ice crystals increases with crystal size reduction faster than the infrared emittance (Zhang et al 1999). Overall, the increase in contrail occurrence and the lower albedo of contrails forming in the biofuel case outweigh the cooling effect of optical depth reduction, caused by its prevailing effect on longwave versus shortwave radiation. This leads to a higher average net radiative forcing of between 0% and +18% for all cases except plate crystals, which show a 4% reduction in net RF. This is contrary to expectations of a substantial RF benefit associated with the decrease in optical depth (e.g. Kärcher (2016)).

The contrast between the cooling effect brought by contrail optical depth reduction and the warming effect due to contrail albedo reduction is shown in figures 2(a) and (b) and figures 3(a) and (b) assuming spherical ice crystals, displaying daytime (RF$_{day}$) and nighttime (RF$_{night}$) components of radiative forcing for the conventional and biofuel cases. Compared to conventional fuel, use of paraffinic biofuels increases daytime radiative forcing between 56% and 550% (figure 2(b)) and decreases nighttime RF between 6% and 31% (figure 3(b)).

Comparing the clean burn case ($E_{IN} = 0.90 \times 10^{13}$ kg$^{-1}$) with the baseline emission case ($E_{IN} = 2.63 \times 10^{15}$ kg$^{-1}$), the reduction of suitable IN

![Figure 1](image_url)
emissions results in changes in contrail properties similar to the ones produced by alternative fuels. On average, contrails in the clean burn case are characterized by larger crystals (+43%) at smaller number concentration (−67%) with respect to the baseline case. The resulting contrail optical depth is therefore decreased (−27%), but this cooling effect is again counterbalanced by the lower planetary albedo change induced by contrails (−33%). The effect on net radiative forcing (figure 4(c)) is less clear than the biofuel case, ranging between 13% lower and 5% higher than the conventional fuel case. This result shows that, since the decreased albedo (reverse Twomey effect) offsets most of the benefits of reducing longwave RF, even substantial reductions in IN emissions offer, at best, limited potential for reducing contrail warming.

4. Discussion and conclusion

The Contrail Evolution and Radiation Model (CERM) has been used to evaluate the effects of changes in aircraft fuels and emissions on contrail warming using scenarios which consider reductions in ice nuclei emissions either from the use of paraffinic biofuels (or other paraffinic alternative fuels) or through improvements in combustor technology which decrease soot emissions. In the case of biofuels, contrails are found to form more frequently due to the higher water emissions index of paraffinic fuels, and this leads to a change in net RF of −4 to +18% compared to conventional fuels (figures 4(a) and 4(b)). This effect is composed of an increase in daytime RF (+10 to +22 mW m⁻²) and a decrease in nighttime RF (−6 to −21 mW m⁻²), so by selectively using biofuels.
at night, a reduction in contrail RF could be achieved. In contrast, for cleaner burning engines, which would operate at all times of day, the increase in daytime RF (+8 to +17 mW m$^{-2}$) and a decrease in nighttime RF (−11 to −21 mW m$^{-2}$) nearly cancel out, leaving a net change in contrail RF of −5 to +4 mW m$^{-2}$.

This suggests that advances in combustor technology which reduce soot emissions may not contribute to a significant reduction in contrail RF.

Modeling contrails requires capturing several complex phenomena from plume-scale growth to the microphysical aspects of contrails and their interaction with light. Assumptions are made and parameter values used throughout CERM that can alter the results of individual simulations, so there is uncertainty in the results presented in this paper. A major source of uncertainty is the choice of ice crystal habit (Schumann et al 2012) and the range of RF values presented in this paper portray the effect of varying this assumption. Paired comparisons among simulations using the same ice crystal habit show that paraffinic (such as HEFA and FT) biofuels have a net warming effect in all cases except for plate crystals, while the effect of a clean burning engine is more varied. The sensitivity of the results shown in this paper to assumptions in the microphysical modeling suggest that further development of these models is warranted in order to understand and reduce the uncertainties associated with contrail modeling. Such model improvements are especially important at a time when the characteristics of aircraft emissions are changing through the adoption of biofuels and advancements in engine technology.
Figure 4. Average net radiative forcings from contrails and contrail cirrus over the United States assuming spherical ice crystals for all the fuels/emissions cases investigated in this study. Results are shown for: net RF for the Conventional Jet emission case (a), net RF for the paraffinic biofuel emission case (b), net RF for the Conventional Jet Clean Burn case (c). RF<sub>net</sub> absolute values below 4 mW m<sup>-2</sup> are not displayed.

Acknowledgments

We thank C Rojo for providing the meteorological and flight data used in the contrail model, B Sridhar, N Chen and J Li for the contributions to the preliminary stages of model setup, and S Eastham for the valuable discussions and inputs to define the model testing configurations. This research was supported in part by NASA under cooperative agreement NNX14AT22A.

References

Alduchov O A and Eskridge R E 1996 Improved magnus form approximation of saturation vapor pressure J. Appl. Meteorol. 35 601–9
Burkhardt U and Kärcher B 2011 Global radiative forcing from contrail cirrus Nat. Clim. Change 1 54–8
Cumpsty N 2003 Jet Propulsion (Cambridge: Cambridge University Press)
Cziczo D J and Froyd K D 2014 Sampling the composition of cirrus ice residuals Atmos. Res. 142 15–31
DeMott P J, Prenni A J, Liu X, Kreidenweis S M, Petters M D, Twohy C H and Rogers D C 2010 Predicting global atmospheric ice nuclei distributions and their impacts on climate Proc. Natl Acad. Sci. 107 11217–22
DeMott P J, Möhler O, Stetzer O, Vah G, Levin Z, Petters M D and Saunders C 2011 Resurgence in ice nuclei measurement research Bull. Am. Meteorol. Soc. 92 1623–35
Durdina L, Brem B T, Abeggen M, Lobo P, Rindlisbacher T, Thomson K A and Wang J 2014 Determination of PM mass emissions from an aircraft turbine engine using particle effective density Atmos. Environ. 99 500–7
Gierens K, Spichtinger P and Schumann U 2012 Ice Supersaturation, in: Atmospheric Physics—Background—Methods—Trends ed U Schumann (Berlin: Springer) (https://doi.org/10.1007/978-3-642-30183-4)
Hartmann D L, Ockert-Bell M E and Michelsen M L 1992 The effect of cloud type on Earth’s energy balance: global analysis J. Clim. 5 1281–304
Haywood J M, Allan R P, Bornemann I, Forster P M, Francis P N, Milton S and Thorpe R 2009 A case study of the radiative forcing of persistent contrails evolving into contrail-induced cirrus J. Geophys. Res. Atmos. 114 D24201

Hendricks J, Kärcher B, Döpelheuer A, Feichter J, Lohmann U and Baumgardner D 2004 Simulating the global atmospheric black carbon cycle: a revisit to the contribution of aircraft emissions Atmos. Chem. Phys. 4 2521–41

Holzäpfel F and Gerz T 1999 Two-dimensional wake vortex physics in the stably stratified atmosphere Aerosp. Sci. Technol. 3 261–70

IPCC 2013 Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge and New York: Cambridge University Press)

Irvine E A and Shine K P 2015 Ice supersaturation and the potential for contrail formation in a changing climate Earth Syst. Dyn. 6 555–68

Kalogirou S A 2014 Solar Energy Engineering 2nd edn (Oxford: Academic)

Kärcher B 2016 The importance of contrail ice formation for mitigating the climate impact of aviation J. Geophys. Res. Atmos. 121

Kärcher B and Yu F 2009 Role of aircraft soot emissions in contrail formation Geophys. Res. Lett. 36 L01804

Kärcher B, Busen R, Petzold A, Schroeder F, Schumann U and Jensen E 1998 Physicochemistry of aircraft-generated liquid aerosols, soot, and ice particles. 2. comparison with observations and sensitivity studies J. Geophys. Res. 103 17129–47

Lewellen D C and Lewellen W S 2001 The effects of aircraft wake dynamics on contrail development J. Atmos. Sci. 58 391–406

Li J, Caaazzo F, Chen N Y, Sridhar B, Ng H and Barrett S 2013 Evaluation of aircraft contrails using dynamic dispersion model AIAA Guidance, Navigation, and Control (GNC) Conf. pp 2013–5178

Moore R H, Thornhill K L, Weinzierl B, Sauer D, D’Ascoli E, Kim J and Anderson B E 2017 Biofuel blending reduces particle emissions from aircraft engines at cruise conditions Nature 543 411–5

Murphy D M and Koop T 2005 Review of the vapour pressures of ice and supercooled water for atmospheric applications Q. J. R. Meteorol. Soc. 131 1539–65

NASA Langley Research Center Atmospheric Science Data Center 2015 CERES SYN1deg Observed Radiative Fluxes and Clouds with Computed Profile Fluxes (http://gcmd.nasa.gov/records/GCMD_CERES_SYN1deg-3Hour_Terra-Aqua-3A.html)

National Oceanic and Atmospheric Administration Earth System Research Laboratory 2015 Rapid Refresh (http://rapidrefresh.noaa.gov/)

Petzold A, Stein C, Nyeki S, Gysel M, Weingartner E, Baltensperger U and Wilson C W 2003 Properties of jet engine combustion particles during the PartEmis experiment: microphysics and chemistry Geophys. Res. Lett. 30 1719

Ponater M, Marquart S and Sausen R 2002 Contrails in a comprehensive global climate model: Parameterization and radiative forcing results J. Geophys. Res. Atmos. 107 ACL 2–1–25

Pruppacher H and Klett J 2010 Microphysics of Clouds and Precipitation vol 18 (Dordrecht: Springer Science and Business Media)

Schumann U 2012 A contrail cirrus prediction model Geosci. Model Dev. 5 543–80

Schumann U, Mayer B, Graß K and Mannstein H 2012 A Parametric Radiative Forcing Model for Contrail Cirrus J. App. Meteorol. Climatol. 51 1391–406

Schumann U 1996 On conditions for contrail formation from aircraft exhausts Meteorol. Z. 5 4–23

Schumann U and Graf K 2013 Aviation-induced cirrus and radiation changes at diurnal timescales J. Geophys. Res. Atmos. 118 2404–21

Seinfeld J H and Pandis S N 2016 Atmospheric Chemistry and Physics: from Air Pollution to Climate Change (Hoboken, NJ: Wiley)

Speth R L, Rojo C, Malina R and Barrett S R H 2015 Black carbon emissions reductions from combustion of alternative jet fuels Atmos. Environ. 105 37–42

Stettler M E J, Boies A M, Petzold A and Barrett S R H 2013 Global civil aviation black carbon emissions Environ. Sci. Technol. 47 10397–404

Sussmann R and Gierens K M 1999 Lidar and numerical studies on the different evolution of vortex pair and secondary wake in young contrails J. Geophys. Res. Atmos. 104 D24201

Towler C and Gandrud B W 1998 Electron microscope analysis of residual particles from aircraft contrails Geophys. Res. Lett. 25 1359–62

Twayno R 2015 On the planetary albedo Atmos. Environ. 8 1251–6

Wilkinson J T, Jacobson M Z, Malwitz A, Balasubramanian S, Wayson R, Fleming G and Lele S K 2010 Analysis of emission data from global commercial aviation: 2004 and 2006 Atmos. Chem. Phys. 10 6391–408

Zhang Y, Macke A and Albers F 1999 Effect of crystal size spectrum and crystal shape on stratiform cirrus radiative forcing Atmos. Res. 52 59–75