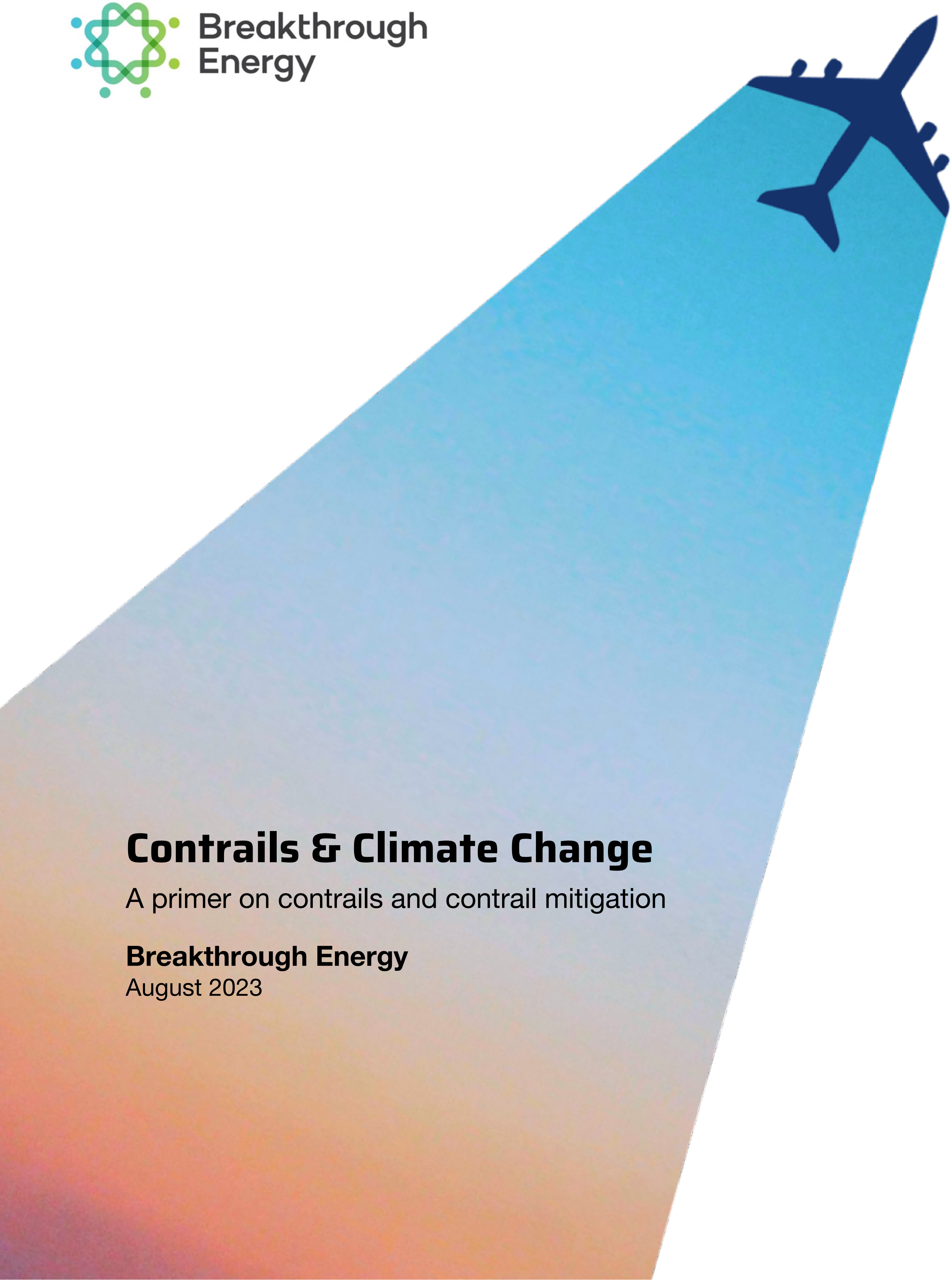

Contrails & Climate Change

A primer on contrails and contrail mitigation

Breakthrough Energy
August 2023

What is this document for?

This article is intended to outline the science of contrails and contrail mitigation for climate scientists and aviation industry professionals. Its main points should be accessible to anyone with a broad scientific background.

We explain how contrails form and evolve, and how the warming effects of contrails are modeled and understood. We provide an overview of how these models are verified through empirical observations. We give an overview of approaches to contrail mitigation including intelligent flight planning, and touch on other approaches such as the deployment of sustainable aviation fuel and cleaner engine technologies.

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Executive Summary

The aviation industry contributes 2.4% of global CO_2 emissions yet it accounts for roughly 3.5% of total anthropogenic global warming. This disproportionate warming impact is primarily driven by condensation trails – or “contrails”.

Contrails are thin ice clouds that form by condensation on jet exhaust plumes. Contrails can grow and become indistinguishable from natural cirrus cloud cover. These clouds weakly reflect incoming solar radiation, but strongly absorb outgoing thermal radiation, causing a net warming effect. In certain conditions, the warming effects of a single dispersed contrail can be much higher than the warming effects of CO_2 emitted from the same flight over 100 years. As few as 2-5% of all flights are responsible for as much as 80% of the warming impact of contrails.

The conditions in which contrails form are predictable from weather forecasts. Contrails can also be observed from satellite and ground-based imagery. The warming effect of a contrail can be estimated by modeling the contrail evolution as it interacts with the surrounding atmosphere. Typically, flights responsible for strongly warming contrails fly within 1000m of trajectories that are much less warming to the climate. Since these harmful regions can be predicted, the warming impacts of aviation can be greatly reduced through intelligent flight planning. Studies have shown that over 80% of the warming impacts of contrails can be reduced through flight diversions at costs as low as 0.1% additional fuel consumption.

In this document, we provide a summary of the science behind contrail formation, evolution, and how the warming effects of contrails are modeled and understood. We provide an overview of how these models are verified through empirical observations. We give an overview of approaches to contrail mitigation including intelligent flight planning, and alternative approaches such as the deployment of sustainable aviation fuel and cleaner engine technologies.

Contrails & Climate Change

How do contrails form?

Contrails are line-shaped ice clouds that form when jet engine exhaust interacts with cold, moist regions of the atmosphere near the tropopause (Figure 1). When the atmospheric relative humidity is high – specifically in regions of ice supersaturation – excess water vapor, ultrafine aerosols, and soot particles in jet exhaust nucleate water droplets that freeze into ice crystals to form contrails. Contrails can persist and evolve in the atmosphere to form high altitude contrail-cirrus clouds. Persistent contrails can last as long as hours, or on rare occasions, days, and can continue to grow and become indistinguishable from natural cirrus clouds.

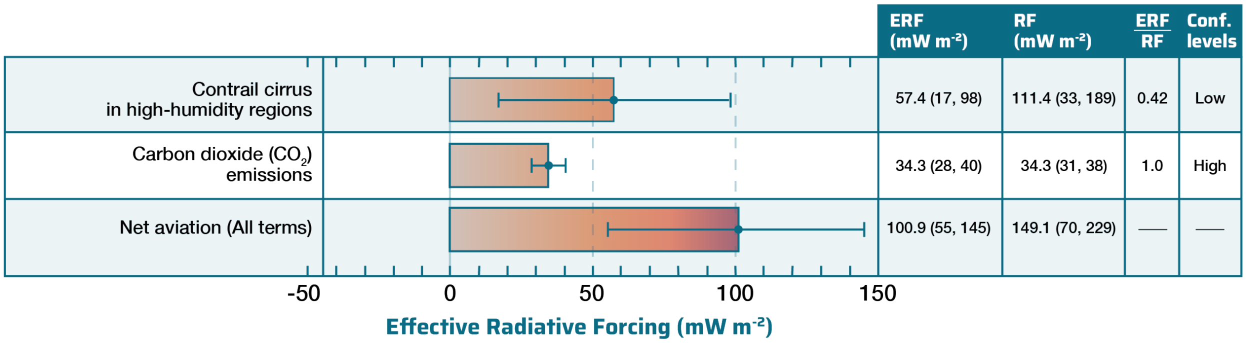
Figure 1. An Airbus A380 from Singapore Airlines leaves condensation trails behind its four jet engines.

How are contrails related to climate change?

Most clouds have a cooling effect on the Earth. However, high-altitude ice clouds, including natural and contrail-induced cirrus clouds, absorb more longwave (thermal) than shortwave (solar) radiation. This means that contrails trap more heat in the Earth's atmosphere than they reflect. The size, shape, and density of the ice crystals within the contrail define its *optical depth* (OD), which determines the extent to which the contrail will reflect *shortwave direct radiation* (SDR) and absorb *outgoing longwave radiation* (OLR). The modified balance of radiation entering and leaving the atmosphere is termed net *radiative forcing* (RF) and is a measure of the instantaneous warming (or cooling) effect of the contrail in units of W m^{-2}.

The total climate effect of a contrail on the atmosphere depends strongly on its evolution and lifetime. Depending on atmospheric conditions, contrails may be short-lived (last for less than 10 mins), persistent (last more than 10 mins), or turn into contrail cirrus clouds (lose their linear shape and take on features of natural cirrus clouds). The net radiative forcing integrated over the contrail area and time quantifies the total energy stored by the contrail, or the contrail *energy forcing* (EF). Energy forcing is expressed in terms of Joules (J), or Joules per meter of trajectory flown (J m^{-1}).

Accurately evaluating the total EF of a single contrail requires a reliable prediction or observation of a contrail's shape and optical properties at every point in time during its life cycle. A contrail may persist for hours after an aircraft has flown its route. Thus, our ability to model and observe contrail evolution is critical to determining the warming impact of a given flight.



	ERF (mW m^{-2})	RF (mW m^{-2})	$\frac{ERF}{RF}$	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	—	—

Figure 2. Recent estimates of climate forcing in 2018 (ERF = effective radiative forcing; RF = radiative forcing) for contrail cirrus and CO_2 contributions to global aviation from 1940 to 2018. Adapted without permission from Lee et al.[1]

A recent study showed the central estimate of contrail-cirrus climate forcing in 2018 was greater than the forcing of all cumulative aviation CO_2 emissions between 1940 to 2018 (Figure 2).[2] The 2022 IPCC report noted that clouds created by contrails account for roughly 35% of aviation's global warming impact.[3] A robust tool for contrail prediction and avoidance would enable us to reduce most of this warming impact using a simple flight planning strategy.

A recent study on Japanese airspace showed that re-routing only 2.2% of flights could reduce 80% of the total energy forcing of aviation activity in that region.[4] A similar study examining flight traffic in the North Atlantic corridor during 2016-2019 showed that 8% of flights cause 80% of the annual contrail energy forcing.[5]

How should we think about the climate impact of contrails relative to CO_2 emissions?

It is difficult to directly compare the warming (climate forcing) effect of contrails to that of CO_2 and other greenhouse gases because their effects are realized over vastly different timescales and spatial domains (Table 1). The warming effect of contrails is caused by short lived, high magnitude radiative forcing in a confined geospatial region (usually several km^2). In contrast, the warming effect of CO_2 is caused by relatively weak radiative forcing (proportional to its atmospheric concentration, measured in ppm) realized over many years. The warming effect of CO_2 is fairly uniform across the planet as CO_2 is well mixed within the upper atmosphere. The heat released due to the combustion of jet fuel also has an instantaneous warming effect on the planet, but this is small compared to the cumulative the effects of contrails and CO_2.[6]

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[1] Lee et al., 2021, "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018."

[2] Lee et al.

[3] Jaramillo et al., 2022, "Chapter 10: Transport."

[4] Teoh et al., 2020, "Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption."

[5] Teoh et al., 2022, "Aviation Contrail Climate Effects in the North Atlantic from 2016 to 2021."

[6] Zhang and Caldeira, 2015, "Time Scales and Ratios of Climate Forcing Due to Thermal versus Carbon Dioxide Emissions from Fossil Fuels."

	Magnitude	Mechanism of Action	Spatial Domain	Time Domain
CO_2	Small	SDR scattering; OLR absorption and re-emission by CO_2 molecules	Very Large (1E8 km^2)	Very Long (decades to centuries)
Contrails	Large	SDR scattering; OLR absorption and re-emission by ice particles	Small (1E1 km^2)	Short (minutes to hours)
Combustion	Small	Direct heating of the atmosphere by heat of reaction	Very Small (<1 km^2)	Very Short (seconds)

Table 1. Factors controlling the climate forcing contributions of contrails, CO2, and heat emissions due to aviation activity.

Due to the non-uniform distribution of these warming forces in both time and space, comparing the net climate impact of each force another is difficult. One approach to placing these forces on an equal footing is to evaluate their cumulative impacts over a fixed time horizon. One commonly used metric is the *Absolute Global Warming Potential* (AGWP)[7] which is the cumulative radiative forcing of a warming force integrated over a specified time horizon. Table 2 shows the relative AGWP of CO2 emissions, contrails, and the heat generated from combustion over several different time horizons. The IPCC states that it is critical to limit the Earth's warming by 2050, and these values clearly show that the effects of contrails are the dominant warming force of aviation within this time horizon.

AGWP[7]	20	50	100	500	1000
CO_2	25.6%	42.1%	55.8%	81.5%	88.2%
Contrails	73.6%	57.2%	43.7%	18.2%	11.7%
Thermal	0.9%	0.7%	0.5%	0.2%	0.1%

Assumptions:

- *Contrail-forming flights are assumed to have a mean contrail EF of 2.68E7 J/m* [8]
- *Mean fuel burn = 7.26 kg fuel km^{-1} (estimate from BADA3)*
- *Mean flight velocity = 800 km h^{-1}*

Table 2. Relative energy forcing contributions of CO_2 emissions, contrail cirrus, and thermal emissions from aviation for various absolute global warming potential time horizons.

How do we predict if a contrail will form and persist?

Persistent contrails and contrail cirrus clouds are generally formed in areas of *ice supersaturation* (ISS). These are cold, moist regions of the atmosphere, where the relative humidity of air with respect to ice is greater than 100%. ISS regions can be identified using numerical weather prediction models such as *European Center on Medium Range Weather Forecasting* (ECMWF) or NOAA's *High-Resolution Rapid Refresh Model* (HRRR). Models predicting the formation, evolution, and lifetime of contrails within these regions have been developed and improved over the course of the last 30 years by combining advances in the modeling of atmospheric and propulsion dynamics.[9]

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[7] Joos et al., 2013, "Carbon Dioxide and Climate Impulse Response Functions for the Computation of Greenhouse Gas Metrics."

[8] Lee et al., 2021, "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018."

[9] Schumann, 2012, "A Contrail Cirrus Prediction Model"; Schumann et al., 2012, "A Parametric Radiative Forcing Model for Contrail Cirrus"; Caiazzo et al., 2017, "Impact of Biofuels on Contrail Warming"; Fritz et al., 2020, "The Role of Plume-Scale Processes in Long-Term Impacts of Aircraft Emissions."

The formation of a persistent contrail can be predicted by the Schmidt-Appleman criterion.[10] Jet engines deposit heat, water vapor, soot particles (derived from aromatics in the fuel), and aerosols (nitrogen, sulfur oxides, and pre-existing atmospheric aerosols). The wake of the aircraft drives turbulent and rapid mixing of the exhaust with ambient air ("wake vortex downwash"), resulting in new equilibrium conditions below the flight's track. If at any time in the process of mixing, cooling, and sinking, this new mixture exceeds *liquid water saturation* conditions, water will condense on soot (or aerosol) particles and quickly freeze into ice crystals, resulting in linear contrails.[11] The contrail will persist if the moisture content of the ambient air around the ice particles stays at or above *ice saturation* conditions. If the temperature increases or the relative humidity falls below ice saturation conditions, the ice crystals sublimate, shrinking and eventually eliminating the contrail.

The Schmidt-Appleman criterion compares the difference in water vapor pressure and temperature between the jet exhaust and the ambient air. For a given aircraft, the ratio of these differences is generally constant, and the line formed by plotting the difference in water vapor pressure as a function of ambient air temperature is referred to as the mixing line:

$$\frac{\Delta e}{\Delta T} = G$$

Here, Δe and ΔT are the differences in water vapor pressure and temperature, respectively, between the exhaust plume and ambient air. The slope of the mixing line, G, is determined by aircraft parameters including the rate of fuel burned, the type of fuel burned, and the engine's efficiency. This relationship is shown in Figure 3, along with curves representing the saturation pressure of both solid water and liquid water. Non-persistent contrails will form when the warm, moist air exiting the jet engine is above the saturation pressure of water but not that of ice. In these cases, water vapor will condense around soot in the aircraft exhaust but will sublimate once cooled to the ambient air temperature. In contrast, if the water vapor pressure is greater than the saturation pressure of ice, the contrail will persist and may form a contrail-cirrus cloud.

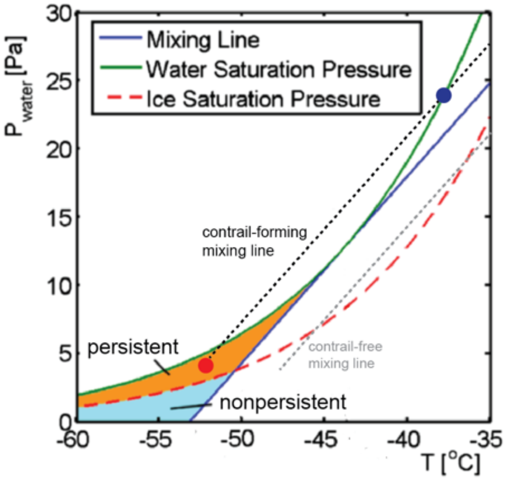

Figure 3. Graphical representation of the Schmidt-Appleman criterion analysis. When the mixing line (representing mixing of engine exhaust and ambient air) crosses the water saturation line, a contrail will form. As the mixture continues to cool and water deposits as ice, the mixing may cease in ice supersaturated conditions (shaded orange) where a contrail will persist. Adapted without permission from Noppel and Singh 2007.[12]

Thus, information about an aircraft's performance, configuration, and flight parameters, combined with knowledge of the temperature and humidity of the surrounding air determines whether a contrail will form and if it will persist in the upper atmosphere.

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[10] Schumann, 1996, "On Conditions for Contrail Formation from Aircraft Exhausts"; Appleman, 1953, "The Formation of Exhaust Condensation Trails by Jet Aircraft."

[11] Kärcher and Yu, 2009, "Role of Aircraft Soot Emissions in Contrail Formation."

[12] Noppel and Singh, 2007, "Overview on Contrail and Cirrus Cloud Avoidance Technology."

Contrail evolution

Estimating contrail climate forcing requires tracking its evolution in time based on the atmospheric conditions. The size, shape, and concentration of ice particles in the contrail affect optical properties that determine how much thermal radiation is absorbed or reflected. The contrail width, depth, and lifetime affect the total area of radiative forcing when integrating contrail energy forcing.

Contrail evolution can be modeled through physical parameterizations and compared with observations from the ground and satellites. Physical models calculate the effective concentration of ice in a contrail as its subject to atmospheric wind, shear, turbulence, and stratification. Atmospheric conditions that influence contrail evolution are pulled from *numerical weather prediction* (NWP) models, such as ECMWF and HRRR.

When contrails first form, the initial number of ice crystals are proportional to the concentration of soot particles in the aircraft exhaust. The initial size of these crystals is largely based on the ambient humidity of the air and the amount of water vapor emitted in the exhaust. These parameters are dependent on the type of jet engine, its operating conditions, and type of fuel.[13]

The water mass content, number of ice particles, and their size and habit (shape) can be parameterized over time as ambient air continually mixes into the contrail plume. The lifetime of a persistent contrail depends on ice particle loss and growth pathways – including particle sublimation due to mixing, particle aggregation due to the sedimentation of larger particles, dilution by ambient air, and sublimation due to mesoscale temperature and humidity fluctuations.[14] Ice habit distribution changes over time as particles grow, affecting the optical properties of the contrail. Contrail extinction is caused by mixing with a mass of air that is too warm or dry to support the existence of ice.

As contrails persist in the atmosphere, they generally disperse laterally due to the advection and diffusion of air in the atmosphere. This process is driven by wind shear and turbulence, which can also act to compress or stretch a linear contrail. Over time, contrails may become visibly indistinguishable from cirrus clouds – these are termed “contrail cirrus” and are responsible for nearly all the warming effects of contrails.

Contrail radiative forcing

The radiative forcing of the contrails can be determined by knowledge of the incident incoming shortwave *solar direct radiation* (SDR) and *outgoing longwave radiation* (OLR), combined with estimates of the *optical depth* (OD), width, and lifetime of the contrail. Optical depth is a ratio of the incident to transmitted radiation through the contrail cloud, accounting for how much radiation is reflected or absorbed. Optical depth is computed using estimates of contrail depth and distribution, size, and shape of ice crystals within the contrail.

During daylight hours, contrails are often found to be slightly warming or slightly cooling due to the significant contribution of *reflected solar radiation* (RSR) on the shortwave radiative forcing function (Figure 4a). During night-time hours, when the absence of sunlight reduces the SDR term to 0, the longwave radiative forcing term becomes dominant. As a result, contrails that persist through the night drive significant absorption and re-emission of outgoing longwave radiation, resulting in strong warming effects (Figure 4b).

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[13] Schumann, 2012, “A Contrail Cirrus Prediction Model.”

[14] Morrison and Gettelman, 2008, “A New Two-Moment Bulk Stratiform Cloud Microphysics Scheme in the Community Atmosphere Model, Version 3 (CAM3). Part I.”

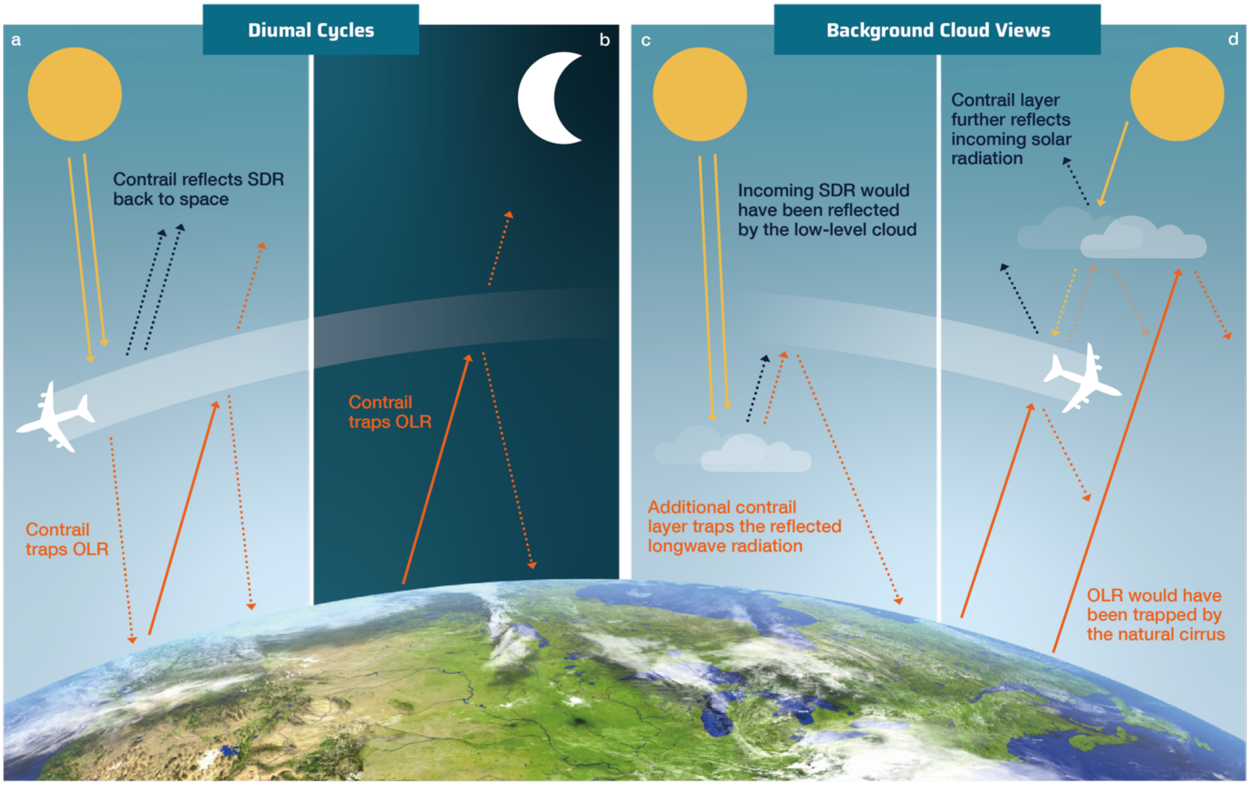

Figure 4. Persistent contrails and contrail cirrus act to modulate radiative forcing by reflecting SDR and absorbing/re-emitting OLR. (a) During the day, contrails act to reflect large amounts of SDR back to space and trap outgoing OLR, resulting in a slightly cooling effect; (b) at night, SDR is 0, resulting in a strongly warming effect due to the dominating effect of trapped OLR; (c) when low-level clouds are present below the contrail, warming effects are amplified as some of the reflected solar radiation from the low-level cloud is trapped by the contrail; (d) when natural cirrus are present above contrails, the radiative forcing effect of contrails is minimized to slightly enhanced reflection of SDR.

Contrail radiative forcing is affected by the presence of clouds (i.e. background cloud fields) above and below the contrail. When clouds are present below, they can enhance warming due to re-emission of reflected long-wave solar radiation from the cloud below; this reflected radiation would have been reflected to space in the absence of the contrail (Figure 4c). When natural cirrus clouds are present above the contrail, they can attenuate the contrail climate effect; the contrail may add a small additional amount of cooling or warming depending on the time of day (Figure 4d). The presence of snow, water, or land under the contrail impacts the OLR incident on the contrail. The total OLR and SDR indecent on a single contrail is taken from values given by NWP models or derived from satellite observations passing over the location.

Persistent contrails and contrail cirrus coverages are as high as 10% in high air traffic areas such as Europe and the east coast of North America.[15] The climate forcing of contrail cirrus varies regionally based on local meteorology, albedo, and air-traffic density. Understanding the aggregate effect of contrail forcing on surface temperature is extremely complex and requires simulation with a climate model, like a *general circulation model* (GCM).

Contrail observations

One of the richest sources of contrail observations is satellite imagery. *Low-earth orbit* (LEO) imagers such as LANDSAT provide high resolution hyperspectral images. Studies from these images have been used to

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[15] Burkhardt and Kärcher, 2011, “Global Radiative Forcing from Contrail Cirrus.”

characterize global contrail coverage and provide empirical estimates of contrail optical properties and their effects on the radiation budget of the earth.[16]

LEO satellites unfortunately only pass over an area of the Earth at most twice a day. This limits their utility in studying contrail evolution or diurnal variations in contrail coverage. *Geostationary orbiting* (GEO) satellites, such as GOES-16 over North America, provide constant observations that enable contrail tracking over time. The spatial resolution of current geostationary satellites is limited to roughly 2 km, diluting optically thin contrails, and making individual contrail detection a challenging task. Studies from GEO satellites have nonetheless proven useful in showing diurnal and seasonal variations in contrail formation and showing correlations between flight density and contrail coverage.[17]

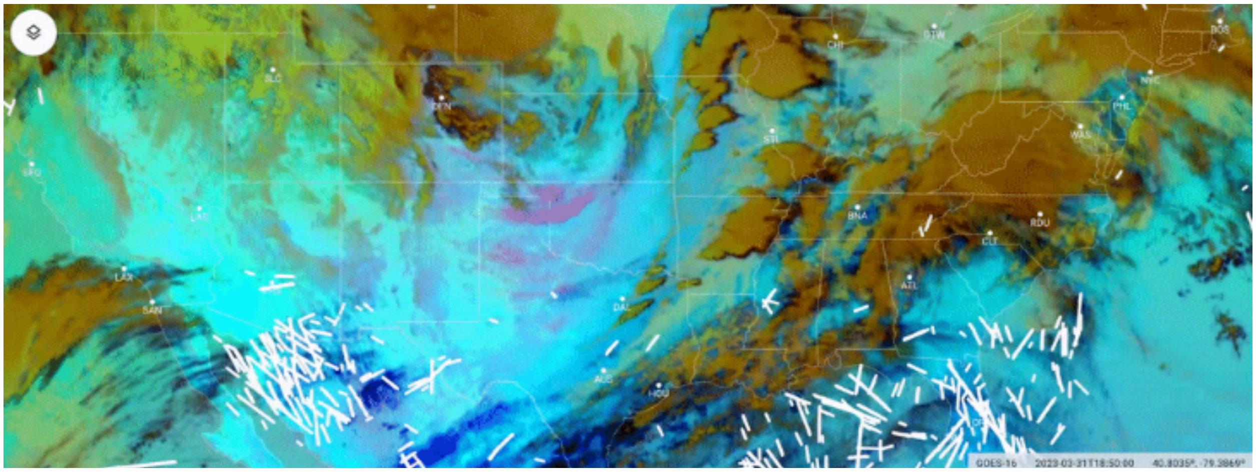

Figure 5. Contrails detected over the United States using Google Research contrail detection model with GOES-16 satellite imagery.[18]

Other studies have explored measuring contrails from sensors on board aircraft. These sensors include optical (LIDAR) sensors, and air samplers that collect information about the size and distribution of ice crystals found in contrails. These studies have been critical in evaluating physical models of contrail formation, evolution, and optical properties. Contrails can also be observed through ground- and space-based LIDAR, and ground-based cameras. These sensors have proven useful in understanding the physical properties of contrails, but are too spatially limited to be used widely.

Contrail mitigation through intelligent flight planning

Categorical avoidance of all persistent contrail forming regions is not feasible. These regions are too large and common, and rerouting around these regions would cause significant impacts in flight times, fuel consumption, and congestion management. However, not all contrails have strong warming impacts, and further, the warming impacts of a single contrail can vary along the length of the contrail. Using contrail prediction tools, we can target the contrail segments that have strong warming impact. Flights responsible for warming typically fly within 1000m of trajectories that are much less damaging. Rerouting planes to higher or lower altitudes would burn less than 0.1% more fuel.[19] In many cases, the warming effect of extra emissions caused by increased fuel burn is offset by reduction of contrail warming.

Avoiding only the most harmful contrail segments can be accomplished by integrating contrail formation models with flight planning software. Harmful contrail forming regions can be served as weather layer much like turbulence or icing (Figure 5). With this data, flight planning software can optimize flight routes

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[16] Duda et al., 2019, "Northern Hemisphere Contrail Properties Derived from Terra and Aqua MODIS Data for 2006 and 2012."
[17] Meijer et al., 2022, "Contrail Coverage over the United States before and during the COVID-19 Pandemic."
[18] Google, 2023, "How AI Is Helping Airlines Mitigate the Climate Impact of Contrails."
[19] Teoh et al., 2022, "Aviation Contrail Climate Effects in the North Atlantic from 2016 to 2021."

to avoid potentially harmful regions when doing so causes only minor changes in fuel consumption or flight time. Automatically accounting for contrails at the flight planning stage reduces the operational burden on airlines and enables rapid fleet-wide adoption of contrail mitigation.

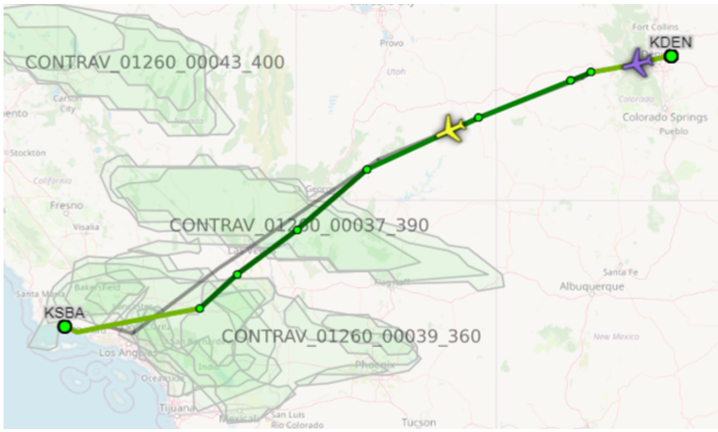

Figure 6. Contrail avoidance regions can be ingested into flight planning software like any other weather layer (e.g. turbulence, icing)

Alternative approaches to contrail mitigation

The newest generation of jet engines for commercial airlines are based on *Double Annular Combustors* (DAC). These engines burn jet fuel more cleanly and efficiently, resulting in a reduction of black carbon emissions by as much as an order of magnitude. Studies have shown that fleet-wide adoption of DAC would reduce the warming impacts of contrails by as much as 70%.[20] These engines are currently being installed on new commercial airplanes, but it will likely be over a decade before fleet-wide adoption.

Sustainable aviation fuel (SAF) is a biofuel produced from sustainable feedstocks that has similar chemical properties to traditional jet fuel. The primary advantage to replacing traditional jet fuel with SAF is a reduced carbon impact. As an added benefit, SAF has a lower concentration of aromatic compounds, leading to a reduction in black carbon emissions. However, emissions from SAF-burning engines contain a much higher water vapor content. Currently, commercial flights can use a blend of up to 50% SAF, and studies have shown that this leads to a reduction of 50% to 70% in soot emission. Contrails produced by planes burning a SAF blend have been shown to be optically thinner.[21] However, the increased water content in SAF exhaust results in a higher rate of contrail occurrence, which may offset the benefit of reduced optical depth.[22] In 2019, only 0.1% of all aviation fuel was SAF, a number that is forecasted to increase to only 2% by 2030.

It is worth emphasizing that both these alternative approaches require large capital investment and fleet-wide adoption of new hardware and fuel technologies. These adaptations will likely take decades to be fully implemented. On the other hand, the climate impact of aviation can be reduced immediately through intelligent flight planning.

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[20] Teoh et al., 2020, “Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption.”

[21] Voigt et al., 2021, “Cleaner Burning Aviation Fuels Can Reduce Contrail Cloudiness.”

[22] Caiazzo et al., 2017, “Impact of Biofuels on Contrail Warming.”

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