



# Aircraft Contrails Factsheet

## Summary

This fact sheet describes the formation, occurrence, and effects of “condensation trails” or “contrails.” It was developed by scientific and regulatory experts at the Environmental Protection Agency (EPA), the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA) in response to public inquiries regarding aircraft contrails. Contrails are line-shaped clouds sometimes produced by aircraft engine exhaust, typically at aircraft cruise altitudes several miles above the Earth’s surface. The combination of water vapor in aircraft engine exhaust and the low ambient temperatures that often exists at these high altitudes allows the formation of contrails. Contrails are composed primarily of water (in the form of ice crystals) and do not pose health risks to humans. They do affect the cloudiness of the Earth’s atmosphere, however, and therefore might affect atmospheric temperature and climate. The basic processes of contrail formation described in this fact sheet apply to both civil and military aircraft.

## What are contrails?

Contrails are line-shaped clouds or “condensation trails,” composed of ice particles, that are visible behind jet aircraft engines, typically at cruise altitudes in the upper atmosphere<sup>1</sup>. Contrails have been a normal effect of jet aviation since its earliest days. Depending on the temperature and the amount of moisture in the air at the aircraft altitude, contrails evaporate quickly (if the humidity is low) or persist and grow (if the humidity is high). Jet engine exhaust provides only a small portion of the water that forms ice in persistent contrails. Persistent contrails are mainly composed of water naturally present along the aircraft flight path.

## How are aircraft emissions linked to contrail formation?

Aircraft engines emit water vapor, carbon dioxide (CO<sub>2</sub>), small amounts of nitrogen oxides (NO<sub>x</sub>), hydrocarbons, carbon monoxide, sulfur gases, and soot and metal particles formed by the high-temperature combustion of jet fuel during flight. Of these emittants, only water vapor is necessary for contrail formation. Sulfur gases are also of potential interest because they lead to the formation of small particles. Particles suitable for water droplet formation are necessary for contrail formation. Initial contrail particles, however, can either be already present in the atmosphere or formed in the exhaust gas. All other engine emissions are considered nonessential to contrail formation.

<sup>1</sup>This fact sheet focuses on contrails produced by aircraft engine exhaust. However, the term “contrail” is also used to refer to the short trails sometimes briefly appearing over aircraft wings or engine propellers, especially under mild, humid conditions. These contrails consist entirely of atmospheric water that condenses as a result of local reductions in pressure due to the movement of the wing or propeller.

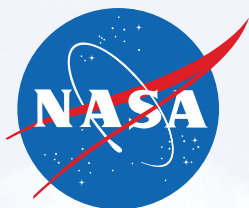




Figure 1. Contrails forming behind the engines of a Lufthansa Airbus A310-330 cruising at an altitude of 35,100 ft (10.7 km) as seen from research aircraft. (Photo: German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt (DLR)), Oberpfaffenhofen, Germany.) Inset: Contrails forming behind the engines of a large commercial aircraft. Typically, contrails become visible within roughly a wingspan distance behind the aircraft. (Photo: Masako Imai, Cloud Castle/Photo Sky Japan.)

## How do contrails form?

**F**or a contrail to form, suitable conditions must occur immediately behind a jet engine in the expanding engine exhaust plume. A contrail will form if, as exhaust gases cool and mix with surrounding air, the humidity becomes high enough (or, equivalently, the air temperature becomes low enough) for liquid water condensation to occur. The level of humidity reached depends on the amount of water present in the surrounding air, the temperature of the surrounding air, and the amount of water and heat emitted in the exhaust.

Atmospheric temperature and humidity at any given location undergo natural daily and seasonal variations and hence, are not always suitable for the formation of contrails.

If sufficient humidity occurs in the exhaust plume, water condenses on particles to form liquid droplets. As the exhaust air cools due to mixing with the cold local air, the newly formed droplets rapidly freeze and form ice particles that make up a contrail (See Figure 1). Thus, the surrounding atmosphere's conditions determine to a large extent whether or not a contrail will form after an aircraft's passage. Because the basic processes are very well understood, contrail formation for a given aircraft flight can be accurately predicted if atmospheric temperature and humidity conditions are known.

After the initial formation of ice, a contrail evolves in one of two ways, again depending on the surrounding atmosphere's humidity. If the humidity is low (below the conditions for ice condensation to occur), the contrail will be short-lived. Newly formed ice particles will quickly evaporate as exhaust gases are completely mixed into the surrounding atmosphere. The resulting line-shaped contrail will extend only a short distance behind the aircraft (See Figure 2).

If the humidity is high (greater than that needed for ice condensation to occur), the contrail will be persistent. Newly formed ice particles will continue to grow in size by taking water from the surrounding atmosphere. The resulting line-shaped contrail extends for large distances behind an aircraft (See Figures 2 and 3). Persistent contrails can last for hours while growing to several kilometers in width and 200 to 400 meters in height.

Contrails spread because of air turbulence created by the passage of aircraft, differences in wind speed along the flight track, and possibly through effects of solar heating.

## What are the ingredients of jet fuel, and are they important to contrail formation?

**A**ll jet fuel is a hydrocarbon mixture containing small amounts of impurities and additives. All aircraft jet fuel is analyzed for strict impurity limits before use. The hydrocarbon content of jet fuel produces water vapor as a by-product of combustion. Contrails would not form behind aircraft engines without the water vapor by-product present in exhaust.



Figure 2. Photograph of two contrail types. The contrail extending across the image is an evolving persistent contrail. Shown just above it is a short-lived contrail. Short-lived contrails evaporate soon after being formed due to low atmospheric humidity conditions. The persistent contrail shown here was formed at a lower altitude where higher humidity was present. Inset: Another example of a short-lived contrail. (Photos: J. Holecek, NOAA Aeronomy Laboratory, Boulder, CO.)

A common impurity in jet fuel is sulfur (~0.05% by weight), which contributes to the formation of small particles containing various sulfur species. These particles can serve as sites for water droplet growth in the exhaust and, if water droplets form, they might freeze to form ice particles that compose a contrail. Enough particles are present in the surrounding atmosphere, however, that particles from the engine are not required for contrail formation. There are no lead or ethylene dibromide additives in jet fuel. Additives currently used in jet fuels are all organic compounds that may also contain a small fraction of sulfur or nitrogen.



Figure 3. Persistent contrails and contrails evolving and spreading into cirrus clouds. Here, the humidity of the atmosphere is high, and the contrail ice particles continue to grow by taking up water from the surrounding atmosphere. These contrails extend for large distances and may last for hours. On other days when atmospheric humidity is lower, the same aircraft passages might have left few or even no contrails. (Photo: L. Chang, Office of Atmospheric Programs, U.S. EPA.)

## Why are persistent contrails of interest to scientists?

Persistent contrails are of interest to scientists because they increase the cloudiness of the atmosphere. The increase happens in two ways. First, persistent contrails are line-shaped clouds that would not have formed in the atmosphere without the passage of an aircraft. Secondly, persistent contrails often evolve and spread into extensive cirrus cloud cover that is indistinguishable from naturally occurring cloudiness (See Figure 3). At present, it is unknown how much of this more extensive cloudiness would have occurred without the passage of an aircraft. Not enough is known about how natural clouds form in the atmosphere to answer this question.

Changes in cloudiness are important because clouds help control the temperature of the Earth's atmosphere. Changes in cloudiness resulting from human activities are important because they might contribute to long-term changes in the Earth's climate. Many other human activities also have the potential of contributing to climate change. Our climate involves important parameters such as air temperature, weather patterns, and rainfall. Changes in climate may have important impacts on natural resources and human health. Contrails' possible climate effects are one component of aviation's expected

overall climate effect. Another key component is carbon dioxide (CO<sub>2</sub>) emissions from the combustion of jet fuel. Increases in CO<sub>2</sub> and other "greenhouse gases" are expected to warm the lower atmosphere and Earth's surface. Aviation's overall potential for influ-

encing climate was recently assessed to be approximately 3.5 percent of the potential from all human activities (See Box 1).

Persistent line-shaped contrails are estimated to cover, on average, about 0.1 percent of the Earth's surface (Sausen et al., 1998; see Figure 4). The estimate uses:

- meteorological analysis of atmospheric humidity to specify the global cover of air masses that are sufficiently humid (low enough atmospheric temperature) for persistent contrails to form
- data from 1992 reported aircraft operations to specify when and where aircraft fly
- an estimated average for aircraft engine characteristics that affect contrail formation
- satellite images of certain regions of the Earth in which contrail cover can be accurately measured (See Figure 5)

The highest percentages of cover occur in regions with the highest volume of air traffic, namely over Europe and the United

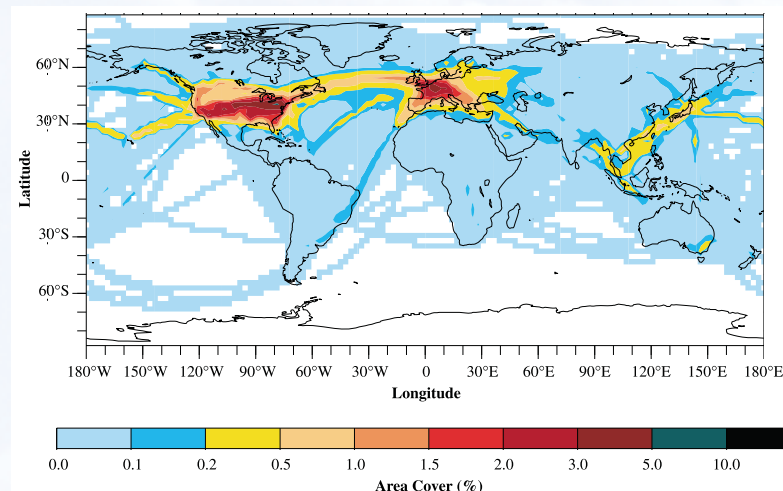


Figure 4. Estimated global persistent contrail coverage (in percent area cover) for the 1992 worldwide aviation fleet. The global mean cover is 0.1 percent. See text for description of how this estimate was made. (Reproduced with permission from Sausen et al., 1998, Figure 3, left panel.)

States (See Figure 4). This estimate of contrail cloudiness cover does not include extensive cirrus cloudiness that often evolves from persistent line-shaped contrails. Some evidence suggests that this additional cirrus cloudiness might actually exceed that of line-shaped cloudiness.

## How is contrail coverage expected to change in the future?

Contrail cover is expected to change in the future if changes occur in key factors that affect contrail formation and evolution. These key factors include aircraft engine technologies that affect emissions and conditions in the exhaust plume; amounts and locations of air traffic; and background atmospheric humidity conditions. Changes in engine fuel efficiency, for example, might change the amount of heat and water emitted in the exhaust plume, thereby affecting the frequency and geographical cover of contrails. Changes in air



Figure 5. Satellite photograph showing an example of contrails covering central Europe on May 4, 1995. The average cover in a photograph is estimated by using a computer to recognize and measure individual contrails over geographical regions of known size. Photograph from the National Oceanic and Atmospheric Administration (NOAA)-12 AVHRR satellite and processed by DLR (adapted from Mannstein et al., 1999). (Reproduced with permission of DLR.)

traffic might also affect persistent contrail formation. It is currently estimated that regions of the atmosphere with sufficient humidity to support the formation of persistent contrails cover about 16 percent of the Earth's surface. If air traffic in these regions increases in the future, persistent line-shaped contrail

### BOX 1



## Scientific Assessment of the Global Atmospheric Effects of Aviation



The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) in 1988 to assess the science, technology, and socioeconomic information needed to understand the risk of human-induced climate change. The 1999 IPCC report, "Aviation and the Global Atmosphere," (see References) describes current knowledge regarding aircraft effects on the global atmosphere. The report was compiled by more than 100 authors from 18 countries. Technical experts from the aviation industry, including airlines and airframe and engine manufacturers, worked with atmospheric scientists in creating this report.

The report considers all gases and particles emitted by aircraft into the upper atmosphere. It also examines the

role these gases and particles play in modifying the atmosphere's chemical properties and initiating the formation of contrails and cirrus clouds. Chapter 3 of the IPCC report provides detailed information about contrail formation, occurrence, and persistence. The report also considers how potential changes in aircraft technology; air transport operations; and the institutional, regulatory, and economic framework might affect emissions in the future. It does not address the effects of engine emissions on local air quality near the surface or potential human health effects of engine emissions. The report notes that significant scientific uncertainty is associated with aviation's predicted influence on climate. A report summary is available from the IPCC Web site at <[www.ipcc.ch](http://www.ipcc.ch)>.

cover there will also increase. Overall, based on analysis of current meteorological data and on assumptions about future air traffic growth and technological advances, persistent contrail cover is expected to increase between now and the year 2050.

## Are persistent contrails harmful to the public?

**P**ersistent contrails pose no direct threat to public health. All contrails are line-shaped clouds composed of ice particles. These ice particles evaporate when local atmospheric conditions become dry enough (low enough relative humidity). The ice particles in contrails do not reach the Earth's surface because they fall slowly and conditions in the lower atmosphere cause ice particles to evaporate.

Contrail cloudiness might contribute to human-induced climate change. Climate change may have important impacts on public health and environmental protection.

## Do authorities regulate aircraft emissions?

**I**n the United States, some aspects of aviation emissions are regulated through the efforts of several government agencies. The U.S. Environmental Protection Agency (EPA), under the Clean Air Act (CAA) of 1970, has established commercial aircraft engine exhaust emissions standards for certain emittants associated with ground-level air pollution. Jet engine exhaust contains, among other emittants, oxides of nitrogen (NO<sub>x</sub>) and hydrocarbons that contribute to ozone formation. Jet aircraft are one of many sources of these pollutants. Ozone is a prime ingredient of smog in and near cities and other areas of the country. While EPA establishes emissions standards for aircraft, the Federal Aviation Administration (FAA) of the U.S. Department of Transportation (DOT) administers and enforces these standards. This domestic framework for regulating aircraft engine emissions is more fully described in Box 2. Currently, there are no regulations addressing contrails and their atmospheric effects.

### BOX 2

## U.S. Environmental Regulatory Framework for Aircraft Engine Emissions

The Clean Air Act (CAA) directs the U.S. Environmental Protection Agency (EPA) to establish aircraft and aircraft engine emissions standards for any air pollutant that could reasonably endanger public health and welfare. In 1997, EPA aligned U.S. emissions standards (40 CFR Part 87) with engine emissions standards and recommended practices (SARPs) prescribed by the International Civil Aviation Organization (ICAO), a United Nations agency established in 1944 that develops SARPs using the technical support of member states and the aviation community. The United States is an active member of ICAO's Committee on Aviation Environmental Protection, which is responsible for further development of engine emissions standards. In establishing U.S. emissions standards, EPA must consult with the Department of Transportation (DOT) to ensure such regulations' effective dates permit the development

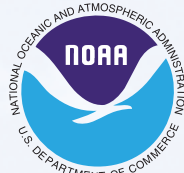
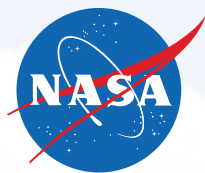
of requisite technology, giving appropriate consideration to compliance cost. It must also consult with DOT concerning aircraft safety before promulgating emissions standards.

Under the CAA, DOT is responsible for enforcing standards established by EPA. DOT delegated enforcement responsibility to the Federal Aviation Administration (FAA). FAA has issued regulations administering and enforcing the emissions standards that apply to civil airplanes powered by gas turbine engines. FAA ensures compliance with these regulations by reviewing and approving certification test plans, procedures, test reports, and engine emissions certification levels. For more information on aircraft emissions or to access EPA's or FAA's aircraft regulations, visit the Aviation Emissions Website of EPA's Office of Transportation and Air Quality at [www.epa.gov/otaq/aviation.htm](http://www.epa.gov/otaq/aviation.htm).

## For further information

Further scientific information about the effects of aircraft on the upper atmosphere can be found in the 1999 IPCC report, "Aviation and the Global Atmosphere" (see References). Information about aircraft and aircraft engine emissions regulations can be found at EPA's aviation emissions Web site, <[www.epa.gov/otaq/aviation.htm](http://www.epa.gov/otaq/aviation.htm)>. Information about military aircraft and military space launch activities, and their atmospheric and environmental effects, can be found at <[http://xre604.brooks.af.mil/safmiq/esoh\\_issues.htm](http://xre604.brooks.af.mil/safmiq/esoh_issues.htm)>. For additional copies or further information on this fact sheet, contact the EPA Stratospheric Protection Hotline at 800 296-1996.

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