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CONTRAILS

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Introduction

One of the most visible anthropogenic effects on the atmosphere is the condensation trail, or contrail. These aircraft-induced clouds have become a common sight since the 1960s because of increasing jet traffic, but they were observed as early as 1919. Contrails were frequently seen and filmed in World War II during bombing raids or dogfights. They were briefly studied in Germany during the war but drew little scientific interest again until the early 1950s when the use of jet aircraft by military and commercial aviation accelerated. Interest waned, with only sporadic studies until the 1990s when aircraft effects and contrails became the foci of numerous research efforts. Concerns over their impact on climate and aircraft visibility have been the primary motivation for the recently intensified research into contrails. Understanding their effects requires knowledge of their physical and optical characteristics and how, when, and where they form.

Contrail Formation

Contrails are generally composed of ice crystals with trace amounts of exhaust products such as soot and sulfates. The contrail ice crystals form because the relative humidity with respect to liquid water, U_w, temporarily reaches the saturation point in the plume mixture of ambient air and hot exhaust gases. Tiny droplets develop on background aerosols or on aerosols formed by exhaust compounds. Because the ambient temperatures required for formation of contrails are generally less than $-40°C$, the small water droplets instantly freeze and grow via vapor-to-ice deposition as long as the relative humidity with respect to ice, U_i, remains above the saturation point. They dissipate via sublimation if U_i is below the saturation point or by precipitation into unsaturated layers below the flight level.

Another type of contrail that forms briefly at warmer temperatures is composed of water droplets that form behind the tips or the leading edges of aircraft wings. These are commonly seen emanating from fighter aircraft in high-speed maneuvers in a humid atmosphere. In these cases, the ambient air is compressed at the wing tip and then expands quickly during adiabatic expansion within the low-pressure area above the wing tip. The expansion temporarily cools the air sufficiently that it falls below the dew point, resulting in condensation. Because ice contrails are the more common variety, the liquid water contrails are not considered further here.

The basic concepts for determining the conditions for contrail formation were developed independently by E. Schmidt in Germany during 1941 and H. Appleman in the United States during 1954. The lines in **Figure 1** schematically illustrate the ice contrail formation process for several scenarios with the ambient temperatures T_a and water vapor partial pressures e_a indicated by the points at the lower end of each line. Each line extends to the temperature T_e and water vapor partial pressure e_e of the exhaust exiting the engine. In cases defined by the lines I, II, and IV, the ambient water vapor pressure is less than the ice saturation partial pressure e_i, while in case III, $e_a > e_i$. In case I, the partial pressure exceeds e_i during the mixing but never reaches water saturation and a contrail does not develop. A short-lived contrail would develop in case II because, at point F, the mixture temperature T_F coincides with the liquid water saturation partial pressure e_w. The contrail would form when the plume temperature reached T_F and would persist until the plume partial pressure decreased to a value below e_i at approximately $-42°C$. A long-lived, persistent contrail would form in case III because the ambient air is supersaturated with respect to ice. Because saturation conditions cover a greater range of temperatures after initial formation, the contrail formed in case IV would probably last longer than that in case II.

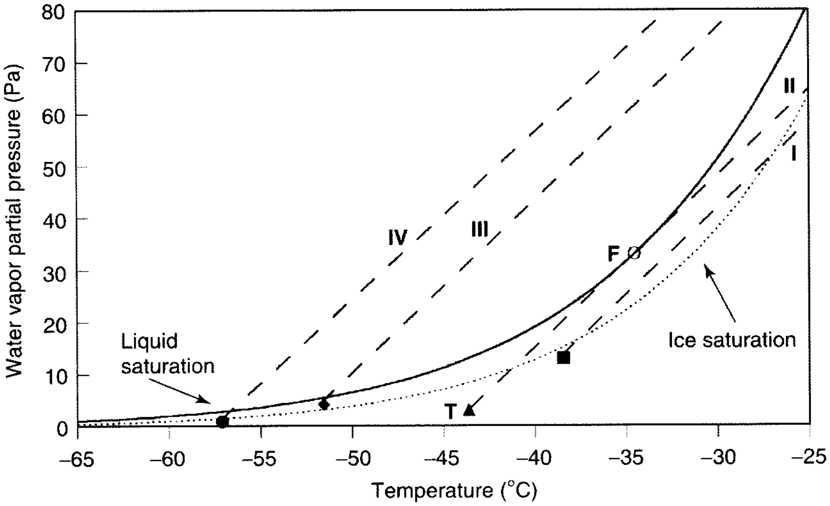

Figure 1 Phase diagram with mixing lines for aircraft exhaust in different ambient conditions.

Although contrail formation has been observed at temperatures as great as –36°C, it is clear from **Figure 1** that contrails form more easily at lower temperatures. The threshold temperature T_T for contrail formation is defined as the warmest ambient temperature that will support contrail formation for a given value of e_a and the exhaust parameters T_e and e_e. The latter quantities determine the mixing line slope, G, and are functions of engine type, operating conditions, and fuel, while the value of e_a can be determined from vertical profiles of atmospheric and dew point temperatures. In case II, the ambient temperature at point T is the contrail formation threshold temperature for the given values of e_a and the mixing line slope G. That is, the ambient temperature enabling contrail formation would have to change if either e_a or G varied and, therefore, T_T is unique for each pair of e_a and G. The threshold temperatures are greater than T_a for cases IV and III, and less than T_a for case I. To find T_T for a particular slope and e_a, it is necessary to determine the tangent point T_F for a line having slope G with the curve describing the variation of e_w with T. Given a value of G, the threshold temperature can be computed for T_F between – 10°C and – 60°C using eqn [1].

$$T_F = -46.46 + 9.43\ \ln(G - 0.053) + 0.720 \times [\ln(G - 0.053)]^2 \qquad [1]$$

where G is given in Pa K^{-1}. The threshold temperature for any value of U_w or e_a can be determined iteratively with eqn [2].

$$T_T = T_F - \frac{e_w(T_F) - U_w e_w(T_T)}{G} \qquad [2]$$

The mixing line slope depends on the specific plume enthalpy h_p and the water vapor mixing ratio q, which, in turn, are related to the emission index EI_w, mass specific combustion heat Q, and the overall engine efficiency η. The relation is given specifically as eqn [3], where c_p is the specific heat capacity, p is the pressure, and $\varepsilon = 0.622$. The emission index, the mass of water produced per mass of combusted fuel, accounts for Δq since $e_e \gg e_a$.

$$G = \frac{\Delta e}{\Delta T} = \frac{(\Delta q/\Delta h_p)pc_p}{\varepsilon} = \frac{EI_w pc_p}{\varepsilon Q(1-\eta)} \qquad [3]$$

The enthalpy differential is also determined almost entirely by Q and η because the ambient heat is negligible compared to that produced by the engine. Since Q and EI_w can be determined for a given fuel, the overall efficiency, the ratio of propulsion energy to total combustion energy is the primary variable affecting the mixing line slope. The slope of the line increases with increasing efficiency. Each type of engine has a nominal efficiency that is based on stationary operating conditions. The overall efficiency, however, may vary for a given engine because of different airframes, maintenance, and operating conditions. **Figure 2** illustrates the impact of efficiency for a given set of ambient conditions. In this instance η_2 is slightly less than η_1, resulting in a contrail from the plane with η_1 and no contrail from the one with η_2. Thus, two planes flying in the same environment can produce two different results. Similarly, a plane might produce a contrail when it is cruising but not when it is ascending, depending on the effect of acceleration on the efficiency.

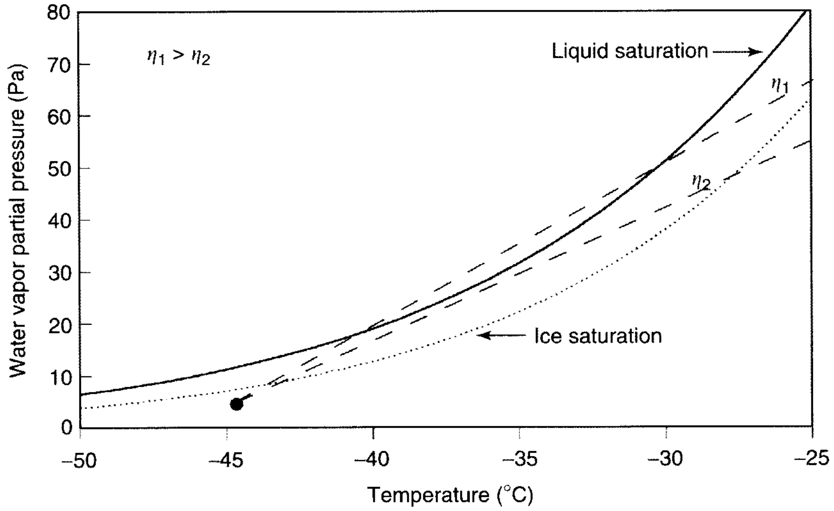

Figure 2 Hypothetical mixing lines for different propulsion efficiencies.

Contrails typically form at a distance of about 30 m or less behind the aircraft engines where the turbulent mixing sufficiently reduces the temperature. The latest research results indicate that the initial condensation of the supercooled droplets takes place on a wide variety of particles, including exhaust products such as sulfate aerosols, soot, and metallic particles as well as ambient mineral aerosols. When the contrails are about 1 minute old, the mean particle radius is around 2 μm. A wide variety of particle shapes have been observed in young contrails, including hexagonal columns and plates, triangles, irregular forms, and spheroids. Young contrails often appear saw-toothed or appear to have a cellular structure that results from the vortices formed by the aircraft. This structure provides irregularities for formation of local convective cells or radiative cooling gradients that aid mixing of the contrail with the ambient air.

Contrail Growth and Structure

Once formed, a contrail develops or dissipates in the same manner as a naturally generated cirrus cloud. Growth and spreading of contrails depend on the thickness of the supersaturated layer, the degree of ice supersaturation, and the wind speed and shear. When contrails persist, the particles typically grow to 30–1000 μm, sizes usually associated with natural cirrus clouds. Ice particle growth is rapid in highly supersaturated layers and results in fall streaks that spread horizontally in lower layers according to the wind shear. **Figure 3A** shows a cross-section view of a hypothetical persistent contrail growing and spreading in the absence of vertical wind shear. It spreads mostly by turbulent mixing induced by the aircraft vortex or by radiative processes. When wind shear is present (**Figure 3B**), it will also spread horizontally by precipitation into the lower layers. If the crystals fall

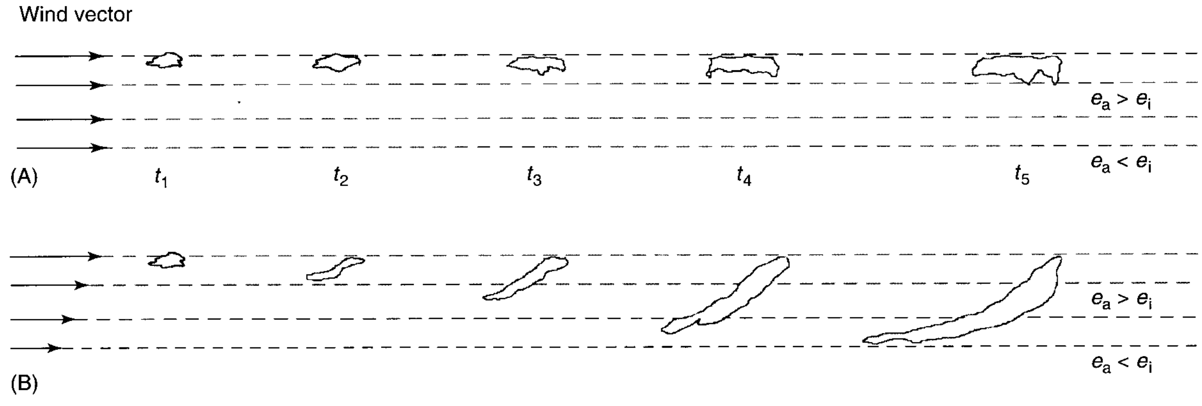

Figure 3 Schematic cross-sectional depiction of contrail spreading in conditions with and without wind shear.

into supersaturated air below, they will continue to grow or, possibly, split into additional crystals. The linear shape of the contrail will be distorted and the contrail will soon look like a natural cirrus cloud to the observer. Well-aged contrails are often indistinguishable from natural cirrus clouds regardless of shear conditions.

Most studies indicate that the number of crystals in a contrail remains constant after formation in supersaturated conditions. Thus, if the contrail precipitates, the contrail cloud at flight level might gradually fade as its particles are depleted. If e_a is just above ice supersaturation, then the crystal growth will be limited and little precipitation will occur. In this case, the contrail may spread slowly by diffusion, maintaining its linear shape for a relatively long time. Because the crystals grow by deposition, the amount of ice water in the contrail increases until the particles fall out or equilibrium is reached between the ice water content and e_i. Such equilibrium conditions generally do not last very long and the contrail eventually dissipates. Although most persistent contrails have visible optical depths between 0.1 and 0.4, the values are highly variable, ranging between 0.03 and 1. The lifetimes of contrails are also extremely variable. Short-lived contrails may only last a few seconds, while some contrail-generated cirrus clouds have been tracked for more than 17 h. The shape, size, optical properties, and life cycle of contrails are highly dependent on their environment, so that a multitude of contrail morphologies can occur. Contrail-cirrus clouds are generally like natural cirrus clouds within a few hours after their formation.

Because water vapor and temperature are not homogeneously distributed, even at relatively small scales ($\sim$100 m), contrails may form or persist in an apparently erratic fashion, as shown in **Figure 4**. For example, an on–off pattern can occur as an aircraft flies through a moist layer disturbed by a vertical wave or even weak convective plumes. The contrails in **Figure 4A** form in the ascending parts of the wave or plume where the temperature of the rising air falls below the threshold temperature, while in the descending portions the air warms and dries, resulting in no contrail formation. Similar patterns can result from a plane ascending or descending through several thin layers that are near saturation but separated by dry layers as in **Figure 4B**. The persistence of a contrail or parts of it depends on the value of e_a relative to e_i along the contrail line. Thus, parts of a contrail may dissipate rapidly while other portions may linger and even grow. The local turbulence induced by the airframe, the atmospheric stability, and the wind vector also affect the morphology of the contrail.

Photographs of the most familiar type, the short-lived new contrail, are shown in **Figure 5**. In both cases, the pair of trails forming behind the aircraft gradually faded. In those situations, e_a is only slightly less than e_i. When e_a exceeds e_i, less familiar shapes can occur. **Figure 6** shows examples of contrails at different stages of growth or persistence at the same time in different parts of the sky. To the north of the observer (**Figure 6A**), contrails remain very thin and wispy at one end and dense and distorted at the other. To the south-east (**Figure 6B**), a succession of slowly spreading contrails appears off to the horizon.

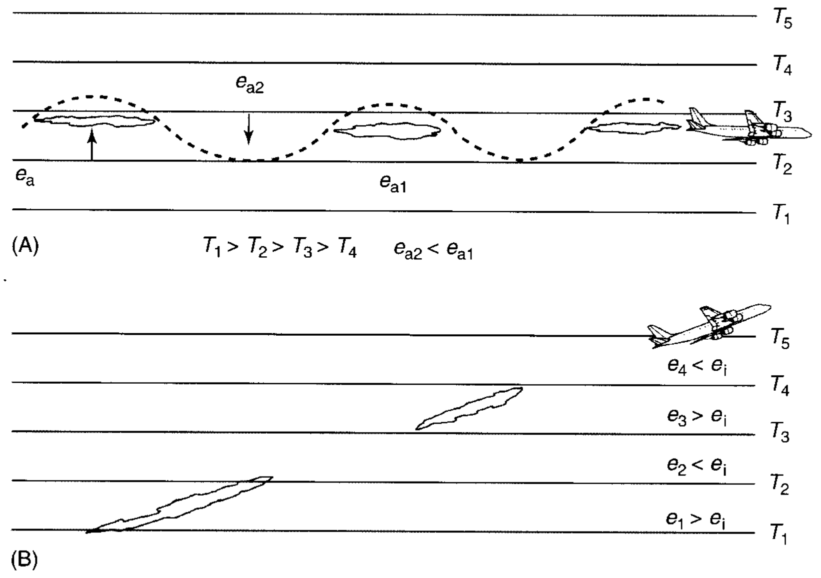

Figure 4 Schematic depiction of contrails forming in an on–off pattern.