1. The Initiation of Aircraft Condensation Trails

a) Contrail initiation by mixing of engine exhaust and environmental air

Aircraft condensation trails ("contrails") are formed by mixing between the engine exhaust air and the surrounding environmental air. The exhaust air contains additional water vapour that has been released by burning fuel and the mixing process creates a plume of air that is briefly super-saturated with water vapour. Observations of contrail formation conditions show that it is necessary to achieve super-saturation with respect to liquid water in order for cloud particles to be nucleated in the mixing plume. This mixing process is shown diagrammatically in Fig.1. Points C and E represent two different sets of environmental conditions with temperatures TC and TE, respectively. The diagonal lines at these points represent mixing lines between the environment conditions and those in the engine exhaust plume. The latter point lies far to the top right, due to the combination of both heat and water vapour produced by burning hydrocarbon fuels.

With the current generation of airliner jet engines, contrail formation typically occurs at temperatures below about -45 deg C, with some dependence on the humidity of the ambient air. At such temperatures, the cloud particles forming in the contrail freeze almost instantaneously to leave a cloud of small ice crystals. The temperature conditions required for contrail formation typically occur at altitudes of 30,000ft and above, the typical altitude for many airliners in cruising flight. They may occasionally form at slightly lower altitudes provided that the temperature and humidity conditions are appropriate.

In a very dry atmosphere, continued mixing between the contrail, which is very turbulent, and the environment can lead to the air becoming sub-saturated, resulting in the cloud particles evaporating. Particle evaporation also takes place due to the

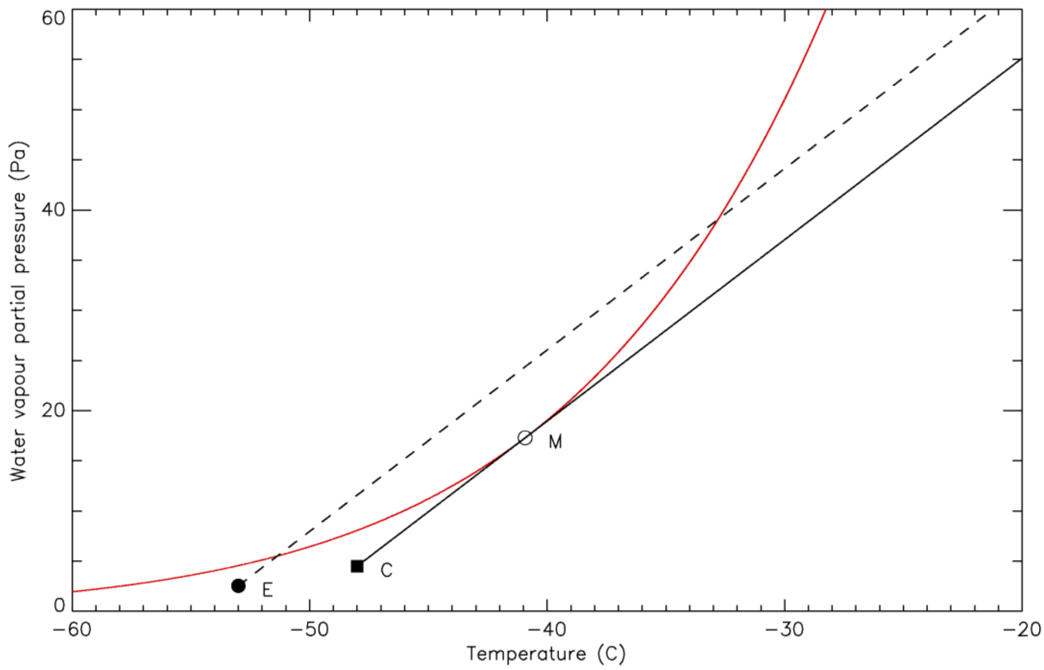

Figure 1 Plume mixing lines and saturation vapour pressure over liquid water. The mixing lines are plotted for environmental conditions with temperature T_E below the critical temperature (point E) and

temperature T_C equal to the critical temperature of the environmental air for contrail formation (point C). The point M is that at which the mixed air is saturated with respect to liquid water (100% RH).

descent (and hence adiabatic warming) as the contrail is entrained into the wingtip vortices. This produces a so-called non-persistent contrail which can be seen to dissipate at some distance behind the aircraft which generated it.

Contrail formation is somewhat analogous to the condensation that can occur in one's breath on a cold day. In this case, mixing between the warm, moist (and nearly saturated) air from the lungs and cold, unsaturated air in the environment can result in a super-saturated mixture in which cloud droplets briefly form.

b) Contrail initiation by condensation over the wing

An additional mechanism for the production of condensation in an aircraft wake is due to the cooling produced by adiabatic expansion of air as it passes through the low-pressure region over the wing. The existence of this low-pressure region is what generates the lift that keeps the aircraft in the air. It may be observed at low altitudes, for example when an aircraft is passing close to the base of a cloud or when it is taking off in warm, humid conditions. In these cases, the adiabatic cooling is sufficient to bring the air to super-saturation with respect to water and this is made visible by the brief appearance of cloud droplets. As the air moves behind the wing and returns to ambient pressure and temperature, the cloud droplets evaporate rapidly and so the cloud formation is only seen in the over-wing region.

Where the aircraft is cruising at a high altitude, it may encounter a region of the atmosphere which is super-saturated with respect to ice but remains sub-saturated with respect to liquid water. In this circumstance, the over-wing adiabatic cooling may then be sufficient to bring the air to water-saturation and droplet formation. Again, liquid droplets formed in these conditions will freeze almost instantly, giving ice particles.

2. Contrail Persistence

In some circumstances, it is possible for the environmental air in which the contrail forms to be at or above the saturation humidity with respect to ice. It should be noted here that the saturation humidity with respect to ice is less than that with respect to liquid water. In this circumstance, mixing between the contrail and the environment does not result in the mixture becoming sub-saturated with respect to ice. Hence, the ice crystals in the contrail can persist for long periods or even grow larger as they absorb the excess water vapour from the environment. This results in a contrail that can persist for many minutes or hours after the passage of the generating aircraft.

There is a wide variety of studies of the existence and formation of such ice-supersaturated but initially cloud-free regions. The super-saturation is generated by adiabatic cooling due to ascent in the absence of any suitable ice-nucleating (IN) aerosol. This lack of IN is likely to be due to their previously having been precipitated out of the air mass during earlier episodes of cloud formation. Spichtinger et al. (2005) describe a case study of the formation of such a cloud-free, ice-supersaturated region. The lifting is forced by the strong ascent at lower levels in the warm conveyor-belt region of an active frontal system. Irvine et al. (2014) present a further analysis of ice-supersaturated regions and their dynamical causes. An understanding of the atmospheric dynamics leading to ice-supersaturation and the triggering of contrail formation along a flight track can be used to model the global formation and distribution of contrail-generated cirrus cloud (Schumann, 2012).

Persistent contrails are not a new phenomenon. There is a large amount of still and cine photo imagery showing persistent contrails produced by combat aircraft during the Second World War. The High-Altitude Flight, which later became the Meteorological Research Flight, was formed in 1942 precisely to investigate the conditions under which contrails formed. The mechanism of persistent contrail formation in these cases was exactly the same as it is now, namely the production of a water-saturated mixture of engine exhaust and environmental air in an environment which is super-saturated with respect to ice.

3. Contrail Spreading

The part of atmosphere in which contrails form (the upper troposphere) can be a region in which strong wind-shear, *i.e*. changes of wind speed or direction with height, occurs. Growing ice crystals in the contrail can, therefore, fall into a layer of the atmosphere in which the wind speed or direction is different from that in its formation layer. This means that the ice crystals can then be carried horizontally away from the contrail. This contrail spreading is most apparent if the contrail is orientated perpendicular to the wind shear direction and can easily result in cloud streaks that may be many kilometres wide and visible in satellite cloud images. In regions of heavy air traffic, it is quite common for the spreading of persistent contrails to result in a thin overcast that covers most of the sky when viewed from the ground. Such overcasts can be difficult to distinguish from natural cirrus cloud. This is also formed in the upper troposphere and is composed of ice crystals.

4. Contrail Intermittency

As noted above, the initiation of contrails is dependent on three major factors, i) the engine exhaust characteristics, ii) the air temperature, and iii) the humidity of the air. At any level in the atmosphere, there may be some variability in the humidity field such that when an aircraft flies along, it may form contrails at one point but not at another. Such structure in the upper tropospheric humidity can result from meteorological phenomena that may be very distant. For example, a thunderstorm can transport water vapour into the upper atmosphere and may leave a plume of moister air that persists and can be transported for long distances after the cloud itself has dissipated.

Day-to-day variability of contrail formation results just from changes in the upper atmospheric temperature and humidity at aircraft flight levels, as the large-scale weather systems evolve. This can give rise to apparent associations between periods of stronger contrail formation and subsequent weather systems, although such associations are entirely natural.

5. The causes of increased persistent contrail activity

A number of inquiries allude to the phenomenon of increased persistent contrail activity over recent years. One obvious cause of this is simply the increase in air transport activity.

However, there is another underlying reason, due to increases in the thermal efficiency of the modern generation of so-called high-bypass turbofan engines.

As noted in 1), contrails are initiated when mixing between the engine exhaust plume and its environment generates a mixture that is saturated with respect to liquid water. The slope, G, of the mixing lines in Fig.1 is given by:

$$G = \frac{\Delta e}{\Delta T} \propto \frac{1}{(1-\eta)} \quad (1)$$

where η is the propulsive efficiency of the engine (Schumann, 1996). This is given by:

$$\eta = FV/(m_f Q) \quad (2)$$

where F is the engine thrust at airspeed V, m_f is the engine fuel flow rate and Q the specific heat of combustion of the fuel. It is clear from this that as engine efficiency increases, then so does G. Hence it is possible for the mixing line to intercept the saturation vapour pressure curve, and hence trigger contrail formation, when it starts at a warmer environmental temperature.

Engine efficiency has been increasing throughout the period of jet aircraft operations, but particularly since the advent of high-bypass turbofan engines in the 1970s. Since contrails may now be generated across a wider range of environmental temperature, it is likely that this has resulted in some part of the observed increases in contrail-induced cloudiness. Schumann et al. (2000) document an experimental observation of differences in the formation of contrails behind two different aircraft with engines of different propulsive efficiency.

6. Colouration in contrails

Many observations of contrails note the appearance of rainbow-like coloured bands within the contrail. The contrail particles are small ice crystals, which may have relatively-pristine crystal shapes, including columns and plates. The refraction phenomena that can be generated by such crystals are well-described in many sources. The theory is given by Liou and Takano (1989). These light-refracting processes lead to the formation of a number of haloes and other optical phenomena. The most commonly-observed are the 22 degree halo and parhelia (or "sun-dogs") but there are many others. It is a feature of such refractions that the deviation of light rays is wavelength-dependent and so white light is separated into colours, completely analogously to what happens in a normal rainbow.

Where the ice particles remain small (less than a few tens of microns in diameter), the deviation of light is due to diffraction. This is also wavelength-dependent and so can lead to colouration of scattered light. Common examples of this that occur principally with liquid cloud droplets are the corona that can appear around the moon or the "glory" that can appear around a shadow cast on the upper surface of cloud or fog, for example by a mountain-top or an aircraft. Very similar phenomena may occur in the immediate formation region of a contrail, where the ice particles are small and remain near-spherical in shape.

7. References

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