Contrails, contrail cirrus, and ship tracks

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ABSTRACT: The following text is an enlarged version of the conference tutorial lecture on contrails, contrail cirrus, and ship tracks. I start with a general introduction into aerosol effects on clouds. Contrail formation and persistence, aviation's share to cirrus trends and ship tracks are treated then.

1 INTRODUCTION

The overarching theme above the notions "contrails", "contrail cirrus", and "ship tracks" is the effects of anthropogenic aerosol on clouds and on climate via the cloud's influence on the flow of radiation energy in the atmosphere. Aerosol effects are categorised in the following way:

- Direct effect: Aerosol particles scatter and absorb solar and terrestrial radiation, that is, they interfere directly with the radiative energy flow through the atmosphere (e.g. Haywood and Boucher, 2000).
- Semidirect effect: Soot particles are very effective absorbers of radiation. When they absorb radiation the ambient air is locally heated. When this happens close to or within clouds, the local heating leads to buoyancy forces, hence overturning motions are induced, altering cloud evolution and potentially lifetimes (e.g. Hansen et al., 1997; Ackerman et al., 2000).
- Indirect effects: The most important role of aerosol particles in the atmosphere is their role as condensation and ice nuclei, that is, their role in cloud formation. The addition of aerosol particles to the natural aerosol background changes the formation conditions of clouds, which leads to changes in cloud occurrence frequencies, cloud properties (microphysical, structural, and optical), and cloud lifetimes (e.g. Lohmann and Feichter, 2005).

Water clouds always form right at water saturation because there are always enough aerosol particles present, so that the vapour can immediately condense and form droplets. The addition of anthropogenic aerosol, for water clouds therefore leads to more numerous but smaller droplets (Twomey effect, Twomey, 1974, 1977). Since radiation scattering gets stronger with decreasing droplet size (when the water mass stays constant) the Twomey effect makes clouds more reflective of solar radiation. Ship tracks are a good example of this effect. Since the droplets get smaller when additional aerosol is present, their tendency to fall relative to the air will be reduced. This weakens the cloud's tendency to form drizzle.

Ice clouds are more complicated than water clouds, because they do not form right at ice saturation. Instead, the natural way of cirrus formation is freezing of supercooled aqueous solution droplets, which needs supersaturations of 45% and more, depending on temperature. Ice nuclei (from anthropogenic sources) that commence to form ice at lower supersaturations may inhibit the build-up of the large supersaturations necessary for freezing of the solution droplets. This generally leads to less and larger ice crystals with a corresponding higher tendency to precipitate. Aerosol particles from aviation could act in this way, but this is yet a hypothesis.

Contrails can form in the blue sky when the ambient air is not supersaturated enough to allow natural formation of cirrus. In the wake of an aircraft, the humidity can reach transiently very high supersaturation, sufficient to let the exhaust particles act as condensation nuclei. Once formed, the contrail ice crystals (at least a fraction of them) can survive as soon as the ambient air is supersaturated. In such a case the contrail can grow laterally into a so-called contrail cirrus, i.e. a naturally

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looking cirrus cloud that would not exist without the prior formation of a contrail. This kind of cirrus formation occurs quite frequently.

2 CONTRAILS AND CONTRAIL CIRRUS

2.1 *Contrail formation*

Contrail formation is like breathing in cold air: Mixing of hot and moist exhaust gases with sufficiently cold ambient air can lead to transient water supersaturation. Exhaust particles and ambient aerosol particles entrained by the vigorous swirling vortex act as condensation nuclei, the supersaturated vapour condenses and quickly freezes in the cooling mixture. Contrail formation takes about 1/3 s.

Whether or not a contrail forms can be decided by the Schmidt-Appleman criterion (Schumann, 1996), a thermodynamic criterion that says that the mixture of the exhaust gases with ambient air must achieve supersaturation with respect to water. In-flight tests of the Schmidt-Appleman criterion have shown its validity (Busen and Schumann, 1995; Jensen et al., 1998; Kärcher et al., 1998). The fact that water saturation must be reached and that ice saturation is not sufficient for contrail formation is due to the poor ice nucleating efficiency of the exhaust particles.

An interesting consequence of the Schmidt-Appleman theory is that modern aircraft can produce contrails in warmer air than old aircraft, that is at lower altitudes (Schumann, 2000; Schumann et al. 2000). The reason behind that is that the exhaust gases of modern, more efficient, engines are cooler than those of old engines (a larger fraction of the fuel energy is used for propulsion), so that water saturation can be achieved in warmer ambient conditions.

Another way of contrail formation is by the aerodynamic cooling of the air flowing over the wing (see Gierens et al., this volume). This process is independent of the Schmidt-Appleman criterion.

2.2 *Contrail-to-Cirrus transition*

The Schmidt-Appleman criterion says only whether or not a contrail can form. It says nothing about the persistence of a contrail. Whether a contrail is persistent or not depends on the ambient relative humidity with respect to ice. One should note that water supersaturation is required only for a fraction of a second during the mixing process to trigger droplet condensation; in principle, a contrail can be formed even in totally dry air, yet a very short one. A contrail can survive until the wake vortices burst (after about 2 min) when the humidity is closer to but below ice saturation. Such a condition can easily be recognized by a ground observer by watching how the contrail evolves into closed rings that quickly vanish. An example is given in Figure 1.

Figure 1. Short non-persistent contrail that forms vortex rings and evaporates then (source: DLR).

Contrail persistence beyond the lifetime of the vortices requires ice supersaturation. Ice supersaturation is a relatively frequent phenomenon in the upper troposphere; it even occurs sometimes in the stratosphere, just above the tropopause. From MOZAIC data we can derive that commercial air traffic routes are about 15% of their way in ice supersaturated air masses (Gierens et al., 1999). Ice supersaturated regions have a mean horizontal extension of 150 km, but specimen with extensions of several thousand kilometres have been found (Gierens and Spichtinger, 2000). Their mean vertical extension is about half a kilometre, at least over Lindenberg in eastern Germany where the measurements took place (Spichtinger et al., 2003). Lifetimes exceeding a day have been found in case studies (Spichtinger et al., 2005), and a few days lifetime of contrail clusters have been found in satellite imagery as well (Bakan et al., 1994).

Contrail-to-cirrus transition starts with the break-up of the vortices. The number of ice crystals that survive the vortex phase is an important initial condition for contrail-to-cirrus transition, as well as the vertical extent and distribution of the ice in the contrail. Both depend strongly on aircraft parameters and ambient conditions, in particular, the degree of supersaturation and temperature. For instance, the fraction of ice crystals surviving the vortex phase is nearly zero just at saturation, and increases to nearly all at about 10-20% supersaturation. Unterstrasser et al. (this volume) give more details on this. The large variability of initial conditions for contrail-to-cirrus transition probably implies a large variation in the properties of the resulting contrail cirrus. The prime mechanism of the transition is spreading of the contrail due to vertical variation of horizontal wind speed, the wind shear. Spreading rates increase with increasing wind shear and with increasing initial vertical extension of the contrail (Dürbeck and Gerz, 1996; Gerz et al., 1998). Horizontal spreading rates ranging from 18 to 140 m/min have been measured with a scanning lidar (Freudenthaler et al., 1995; Freudenthaler, 2000). In a case study, Duda et al. (2004) estimated contrail spreading rates of 2.7 km/h from satellite imagery and weather forecast wind fields.

The later evolution of contrail cirrus depends on the spreading rates and the ambient humidity field. Spreading alone implies dispersion of the ice crystals over a large area, decreasing the optical thickness of the contrail. However, the crystals grow in the supersaturated air, and fresh moisture is mixed into the contrail during the spreading process. The ice mass per crystal increases, and so does the optical thickness. At the same time, the growing crystals may grow enough to eventually fall out of the ice supersaturated region and to evaporate, again decreasing the optical thickness of the contrail cirrus. Usually, persistent contrails don't appear as single objects, and the spreading of several contrails finally leads to a contrail deck (Gierens, 1998) in which the evolution of one contrail cannot be considered separately from the others. Contrail decks also often evolve close to natural cirrus clouds. There is not much known about the evolution of contrail decks nor about the evolution of contrails close to or within cirrus clouds.

2.3 *Aviation's share of cirrus trends*

A long-standing question in relation to air traffic has been whether aviation increases the average cloudiness and whether it affects other weather parameters like daily sunshine duration and temperature range. Here I concentrate on studies that relate aviation with trends of cirrus cloudiness.

Boucher (1999) took ground and ship based cloud observations of the period 1982-1991, grouped into early (1982-1986) and late (1987-1991). He then correlated the late minus early differences of cirrus frequency of occurrence, ΔC, in $3° \times 3°$ grid boxes with the aviation fuel consumption, F, in the same area. He found that essentially ΔC increases with F. Highest ΔC occurred in main air flight corridors, NE USA (+13.3%/decade), and North Atlantic Flight Corridor (+7.1%/decade). Boucher stated that effects of volcanoes, long term changes in relative humidity, or climate variations related to the North Atlantic Oscillation (NAO) could not solely explain the trend in C, nor its regional distribution.

Minnis et al. (2001) performed a similar study, adding satellite data. They found consistency in trends of cirrus and contrails over USA, but not so over Europe, which could point to other important influences on cloudiness, that are stronger in Europe than in USA.

Zerefos et al. (2003) took other potential influence factors into account in their study, namely El Niño Southern Oscillation (ENSO), NAO, and the Quasi Biennial Oscillation (QBO). They deseasonalised the cirrus time series and removed the ENSO, NAO, and QBO signals. Possible effects of changing tropopause temperatures and convective activity were removed by linear regression. Only the residuals were correlated with air traffic. These were found to increase, sometimes statistically significantly, in regions with heavy air traffic, although an overall decrease of cirrus frequency was found. Consistent with Minnis et al., the most significant correlations were found over North America (winter season) and over the NAFC (summer season), while the correlations over Europe were insignificant (at a 95% level).

Stubenrauch and Schumann (2005) studied satellite data (1987-1995) for trends of effective high cloud amount. They introduced a new element in these studies by grouping their data into three classes, according to the retrieved upper tropospheric humidity over ice, UTHi (an average of relative humidity over a thick layer in the upper troposphere, say from 200 to 500 hPa): (1) UTHi high enough for cirrus formation; (2) UTHi not sufficient for cirrus formation, but sufficient for contrail formation; (3) clear sky. It turned out that this additional classification of the data led to a very clear positive trend (+3.7%/decade over Europe, +5.5% over NAFC) in effective high cloud amount, while the overall trend (all classes) was weak.

Stordal et al. (2005) found from an analysis of satellite data (1984-2000) that the time series of cirrus coverage C(t) and air traffic density D(t) (flown distance per km^2 and hour) are generally positively correlated. The correlation is inferred from a linear ansatz: $dC/dt = b\, dD/dt$. Estimated correlations are not strong (partly because other influences have been left in the C(t) time series). They conclude that over Europe aviation produces an extra cirrus coverage of 3 to 5%.

Mannstein and Schumann (2005) also correlated C(t) with D(t), however for 2 months of cirrus data from METEOSAT and actual air traffic data from EUROCONTROL. For relating cirrus cover and traffic density they used an ansatz that takes overlapping of contrails and saturation effects (e.g. finite size of ice-supersaturated regions) into account: $C(t) = Ci(t) + C_{pot}[1-\exp(-D/D^*)]$, where Ci(t) is cover of natural cirrus, C_{pot} is the potential coverage of persistent contrails (Sausen et al., 1998), and the term in square brackets is the fraction of C_{pot} that is actually covered by contrails. It was shown that the relation between additional cirrus coverage and air traffic density indeed followed roughly the exponential model. The main result of this study was that over Europe aviation is responsible for an additional cirrus coverage of 3% (consistent with the result of Stordal et al.). This implies that the mean coverage of contrail cirrus over Europe exceeds the corresponding mean coverage of linear contrails by almost one order of magnitude.

Krebs (2006) extended the study of Mannstein and Schumann, by analysing cirrus coverage and air traffic of 11 months in 2004, for Europe, North Africa, and the North Atlantic. Over this extended region he still found a significant correlation between cirrus coverage and air traffic density. But the air traffic induced cirrus cover was smaller than in the Mannstein and Schumann study, namely 0.6±0.2%. The inclusion of regions with essentially no air traffic of course leads to smaller mean additional cirrus coverage. Krebs also investigated the effect of the additional cirrus on the radiation budget of the earth. He found a warming of 1.1 W/m^2 for the region of interest, a value that is more than eight times larger than the value estimated by Boucher (1999). It is currently not clear how much of the correlation in this work between air traffic and cirrus cloudiness is actually due to a causal relationship. Hence the determination of the radiative forcing of contrail cirrus is fraught with very large uncertainties; studies to resolve the differences and to constrain the error margins are certainly needed.

All these studies suggest that air traffic actually induces additional cirrus clouds which seems plausible. However it is extremely difficult to demonstrate and prove such a correlation because the variation of cirrus cloudiness due to natural influences is much larger than the possible aviation effect. Hence, to look for the latter is like looking for a signal hidden in strong noise.

3 SHIP TRACKS

Ship tracks are a good example of the Twomey effect. The clean marine boundary layer (MBL) contains mainly sea salt and sulphate aerosol with a number density of about 500 cm^{-3}. When these act as condensation nuclei, a water cloud forms with a low number density of relatively large droplets. Ship stacks release a lot of soot (and other) particles into the MBL. A part of them also act as cloud condensation nuclei: more but smaller droplets form. The water content of the clouds is hardly affected. Now, the same water amount has a larger optical effect when it is distributed into more but smaller droplets (like a big block of ice can be translucent while crushed ice is opaque).

Thus, the cloud areas that are contaminated by ship emissions have a signature of higher reflectivity than their surroundings on satellite images, which is used to detect them.

The largest measurement campaign to date devoted to the study of ship tracks was conducted in June 1994 off the coast of California, the so-called Monterey Area Ship Track (MAST) Experiment (Durkee et al., 2000a). It produced the largest dataset so far of direct measurements of the effects of ship emissions on the microphysical and radiative properties of marine stratocumulus clouds as an analogue for the indirect effects of anthropogenic pollution on cloud albedo. An analysis of 131 ship-ship track correlation pairs by Durkee et al. (2000b) gave the following ship track characteristics (mean values ± standard deviation): length 296 ± 233 km, width 9 ± 5 km, age 7.3 ± 6 h (but many tracks get older than 12 h), the head of the ship track is 16 ± 8 km behind or 25 ± 15 min. after the ship. Significant variability of the values around their respective averages may be noted. Ship tracks form in a MBL that is between 300 and 750 m deep, and never deeper than 800 m during MAST. Low level clouds must be close to the surface (less than one km), otherwise ship tracks do not form (Coakley et al., 2000). The relative humidity is usually high, temperature differences between air and see are low, and winds are moderate with wind speeds of 7.7 ± 3.1 m/s. However, statistical distributions of MBL and cloud properties overlap a lot for ship track and non-ship track regions. The statistical significance of the differences in the mean have not been given for the MAST experiment.

Not all ships produce tracks. Ships powered by Diesel units that emit high concentrations of accumulation mode aerosol can produce ship tracks. Ships that produce few particles (e.g. nuclear ships) or particles too small for activation as cloud drops (even if in high concentration) do not produce ship tracks. The most likely, if not the only, cause of the formation of ship tracks is the direct emission of cloud condensation nuclei from the stack of a Diesel powered ship. Still then it needs a cloud layer susceptible to aerosol perturbation, and the atmospheric stability must be such to enable aerosol to be mixed throughout the MBL. Furthermore, not all exhausted particles are active as additional cloud condensation nuclei. The type of fuel burned seems to be more important than the type of ship engine in determining whether a ship will produce a track or not. Ships, burning Marine Fuel Oil (a low-grade oil) or navy distillate fuel (high-grade) produce between 4×10^{15} to 2×10^{16} particles per kg fuel burned. About 12% of the particles from Marine Fuel Oil burning serve as cloud condensation nuclei, whereas burning of higher-grade fuels produces particles that are less efficient as cloud condensation nuclei. Ship exhaust particles are composed primarily from organics, possibly combined with H_2SO_4 generated by gas-to-particle conversion from SO_2. 10% (by mass) are water soluble materials. There is no evidence that salt particles from ship wakes cause ship tracks. Water and heat fluxes do not produce detectable perturbations that have an effect on MBL clouds (Hobbs et al., 2000).

As the droplets in a ship track are smaller than usual in a MBL cloud, their coagulation rate to form larger droplets that eventually precipitate in the form of drizzle is diminished. In other words, ship tracks suppress drizzle formation which affects cloud life time and the budget of latent heat. As drizzle formation causes the transition from closed to open cellular convection (Rosenfeld et al., 2006), this transition does not occur in ship tracks. Analysis of satellite data (Schreier et al., 2006) with comparison between non-ship-track pixels and ship-track pixels shows a large increase in the droplet number concentration from 100 cm^{-3} to 800 cm^{-3}. Since the condensed water mass is probably unaffected by the ship track (the satellite data shows that the liquid water path is hardly affected), the droplet's effective radius experiences a significant decrease of from 12 to 6 µm, a clear indication of the Twomey effect. Accordingly, the optical thickness of unpolluted clouds is 20-30, whereas in the ship track it increases up to 45.

Comparing the ocean regions where ship tracks occur with the regions where ship traffic occurs shows that ship tracks is a very selective phenomenon. The special combination of meteorological conditions necessary for formation of ship tracks is rarely given. Thus the direct radiative impact of ship tracks on the Earth's energy budget is probably small. However, ship emissions can have more diffuse effects on low-level clouds that might be of higher climatic relevance, although much harder to detect. Devasthale et al. (2006) analysed time series of satellite data of the region around the English Channel (an ocean strait with very heavy ship traffic) and detected trends of cloud albedo and top temperature, that were ascribed to increasing ship emissions.

4 CONCLUSIONS

Clouds are of utmost importance in the climate system because of their interaction with the hydrological cycle and the radiant energy flow. The transportation sector may cause changes in cloud coverage and frequency and changes in cloud properties. These influences are exerted via semi-direct and indirect aerosol effects. Research currently is focused on ship and aviation emissions and does not include the impact of road traffic emissions on clouds. This is because of the following two reasons: (1) There are evident cloud effects from both shipping (ship tracks) and aviation (contrails) whereas there are no evident cloud effects from road traffic. (2) The road traffic source is rather diffuse (many cars almost everywhere in Europe) whereas aviation is more regulated and shipping by large vessels is more confined to distinct routes. Their movements are recorded which makes source attribution better identified than it would be the case for road traffic. Nevertheless, future research must take the cloud effects of surface transport and of industrial emissions into account, in order to enable fair comparisons of the effects. The knowledge gained from current research on contrails, contrail cirrus, and ship tracks will certainly help for the future topics.

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