HOW TO AVOID CONTRAIL CIRRUS

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OVERVIEW

The impact of air traffic on climate is dominated by the contribution of aircraft induced cirrus. Hence, any mitigation strategy has to consider the production of contrails and cirrus clouds. Here we use operational radiosonde data with high vertical resolution to estimate the effect of a small change in flight altitudes to avoid flight in ice supersaturated air, hence to suppress contrail and cirrus formation. It is shown that a substantial fraction of contrails and contrail induced cirrus can be avoided by relatively small changes in flight level, due to the shallowness of ice-super-saturation layers.

1. INTRODUCTION

The impact of aviation on climate follows several pathways. Carbon dioxide and water vapour, both effective greenhouse gases, are emitted as well as nitric oxides, which influences the chemical composition of the upper troposphere. Soot and sulphuric oxides add to the ambient aerosol and have an impact on cirrus formation and cloud microphysical properties. Since the IPCC1 special report on "Aviation and the Global Atmosphere" (1999) it is known and widely accepted that contrails and the cirrus clouds evolving out of them have a climate impact comparable to the CO2 from the combustion process. These additional, purely man-made clouds change the radiative forcing of the earth-atmosphere system: they reduce the incoming solar radiation as well as the outgoing thermal radiation in a way that the mean net balance at top of the atmosphere is slightly positive – i.e. they add to the greenhouse effect (Meerkötter et al., 1999). The role of contrail and cirrus formation within the total impact of aviation on climate was confirmed at the Aviation, Atmosphere and Climate (AAC) Conference 2003 (Sausen et al., 2004, Mannstein and Schumann, 2005).

A contrail, consisting of tiny ice particles, forms behind an aircraft if the ambient air is cold enough. The physics of this process is well understood and described by the so-called Schmidt-Appleman criterion (Schmidt, 1941; Appleman, 1953). In its present form (Schumann, 1996) this criterion also shows that any advance in total propulsion efficiency of air-planes will lead to more contrails, as the temperature limit for contrail formation increases when less energy is distributed to the air with the exhaust gases (Schumann et al., 2000, see Fig 1). In dry air the contrails dissolve quickly and their impact is of minor importance, but in moist air which is supersaturated with respect to ice (Ice Super-Saturated Regions - ISSR), the contrails spread, grow by uptake of ambient water vapour, and become ‘contrail cirrus’, These aircraft induced cirrus clouds cannot be distinguished from natural cirrus, neither by ground based nor by satellite observations. In a later stage of their lifetime either the ice particles sediment into dryer layers or the air-mass warms due to subsidence, both effects resulting in evaporation.

FIG 1. Old, less efficient engines (B707, right) release more heat together with the exhaust gases than modern ones (A340, left). Thus the formation of contrails is more probable with more efficient engines

The knowledge on ISSRs in the upper troposphere is still limited, as water vapour measurements in this cold environment are a technical challenge. In the usual synoptic analyses of meteorological models super-saturation is not included. In most weather prediction models ISSRs are not represented (one recent exeption is the model of the ECWMF, see Tompkins et al., 2007), and satellite measurements of water vapour profiles cannot provide the necessary vertical resolution (Gierens et al., 2004), in particular because ice supersaturated layers are only 500 m thick on the average (Spichtinger et al., 2003). For the time being the observation of persistent contrails is a very good indicator for the existence of these supersaturated regions, clearly visible for everyone in the regions with high air traffic density over Europe and the continental USA.

Aviation is not yet affected by international regulations concerning the mitigation of climate impact, but this topic is already under discussion. According to the present knowledge on climate impact of aviation, not only the fossil fuel use, but also the contrail and contrail cirrus formation will have to be considered in such a framework.

An aircraft cannot fly without burning fuel, but it has the possibility to avoid the production of contrails by choosing it’s flight level and route. Here we propose a strategy, which allows to minimize the contrail and therefore also contrail cirrus production without major

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impact on fuel use. This strategy is based on statistics of the vertical extent of layers showing super-saturation of water vapour with respect to ice.

2. THE DATA: RADIOSONDE MEASUREMENTS

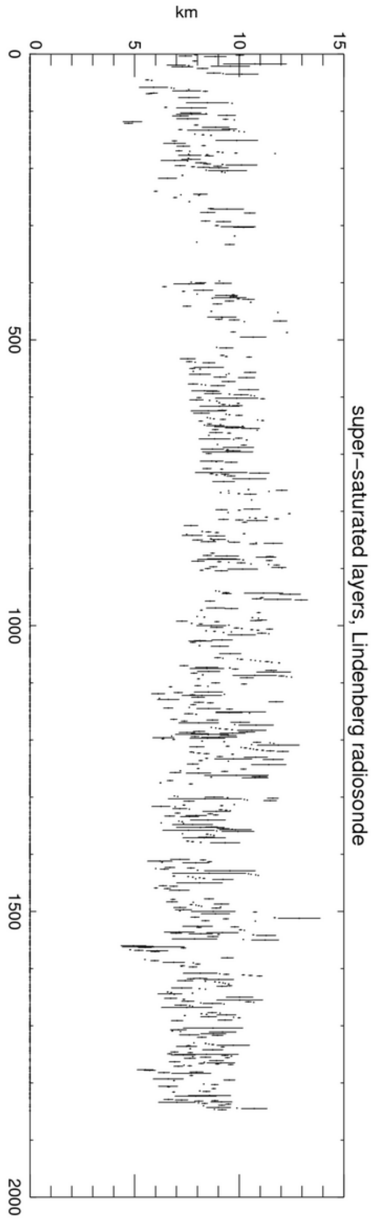

FIG 2. Ice super-saturation over Lindenberg (Feb. 2000 – Apr. 20001)

For this study we use radiosoundings over Lindenberg, Germany. The Lindenberg Observatory of Deutscher Wetterdienst has developed a method that allows to obtain very accurate relative humidities throughout the troposphere and into the lowermost stratosphere (Leiterer et al., 1997). This data can be used to examine the upper troposphere and lowermost stratosphere concerning relative humidity with respect to ice. It was already used in a former study (Spichtinger et al., 2003) for investigation of ice super-saturation over Lindenberg. The data set consists of about 1600 profiles obtained during operational radiosonde ascents from February 2000 to April 2001(See Fig. 1).

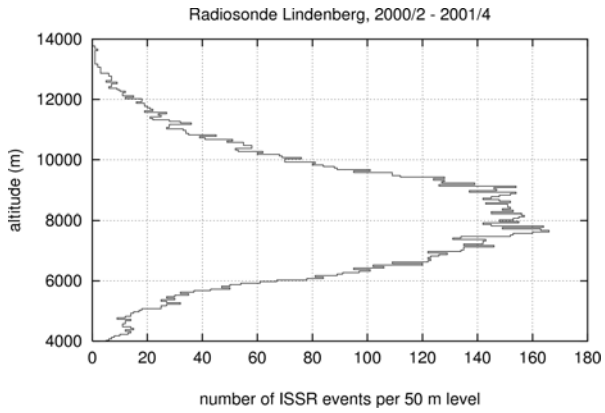

FIG 3. Ice super-saturation over Lindenberg: vertical distribution of ice super-saturated layers

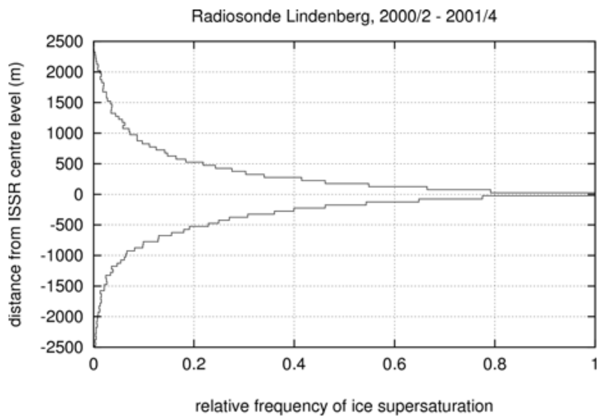

FIG 4. Ice super-saturation over Lindenberg: thickness of the ISS layers

The vertical resolution of the data is about 50 meters. For this data set we cannot distinguish between cloudy and cloud free air, so the term ice supersaturated layer implies both cloud free air and cirrus clouds in the state of super-saturation. Of course this data-set represents only one location and a limited time span. Nevertheless, the assumption that ice-supersaturated layers are similar in their vertical extent throughout the mid-latitudes sounds plausible.

In several studies (e.g. Fichter et al., 2004; Williams et al., 2002, Noland et al., 2004) a general strong reduction of flight altitude has been proposed in order to avoid the climatological maximum of super-saturation with respect to ice which is usually found just below the tropopause (Sausen et al., 1998), in mid latitudes at altitudes around 9 km (~ flight level 290). This is not an optimal strategy, as can be seen in Fig. 5 In this figure we show the relative probability to fly in supersaturated air after a flight-level change from FL 290 for 5 different scenarios. The upper two curves (black and red) show the weak effect of a general flight level shift to higher or lower altitude. For a general upward shift (from FL 290) of up to 15 hecto-ft an aircraft will be even more often in supersaturated air than at FL 290 itself. The blue and green curves show the effect of changing flight altitude on a case-by case basis, i.e. the altitude is only changed when ice-super-saturation is detected. The largest contrail reducing effect with the minimum necessary flight-level change can be reached if it is known, whether the nearest sub-saturated level is in the upward or downward direction (lowest curve, cyan).

3. A POSSIBLE SOLUTION: FLEXIBLE FREE FLIGHT

According to the data-set used in this study a general reduction of flight altitude of at least 6000 ft would be necessary in order to avoid 50% of the contrails. Much more efficient is a strategy of selective flight level change: only if an appropriate instrument (or forecast) signals ice-super-saturation and a positive radiative forcing during the lifetime of the contrail has to be expected it is necessary to act. In this case a change in flight level of less than 2000 ft up- or downwards is generally sufficient to avoid 50% of the contrails. This simple but efficient strategy will work immediately if the pilot has access to an accurate device measuring relative humidity and if there is enough flexibility in the selection of flight levels.

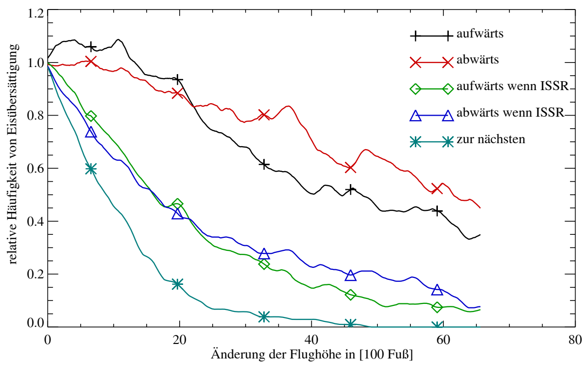

FIG 5. The relative probability to fly still in super-saturated air after a flight-level change from FL 290 for different scenarios (see text)

An even more efficient strategy to avoid contrails would be possible, based on a precise prediction of position and extent of ISSRs. The lowest line in the figure shows that a change by only 1000 ft would be sufficient to reach 50% contrail reduction if the nearest 'dry' layer is known. Within a forecast model it is possible to optimize individual flight profiles not only for fuel consumption but also for least climate impact. This more advanced strategy requires, in addition to the already mentioned free flight possibility and the accurate hygrometer, precise information about the actual state of the atmosphere and its development. To implement the proposed strategies for contrail reduction is a matter of air traffic control, of availability of good hygrometers that function in the cold layers of the tropopause region, and of progress at the aviation weather services in their ability to predict the vertical and horizontal extent of ISSRs. Funded by the German Federal Ministry of Education and Research the project 'Environmental Compatible Flight Route Optimization' started in 2007. In this project the feasibility of such strategies will be evaluated.

Flexible free flight is within the strategies developed by the US and European flight authorities aiming at an improved air traffic management (Bekebrede, 1999; Mulkerin, 2003). Eventually, these strategies aim at reducing fuel costs, but there is no obvious contradiction to the proposed contrail-avoidance strategy.

The detection of super saturation from measurements of ambient temperature and moisture is still a technical challenge, but not impossible, as the MOZAIC2 instrumentation on five passenger aircraft has demonstrated (e.g. Helten et al., 1998). Furthermore, the direct observation of contrails behind an aircraft should be possible with a relatively simple camera system. Additionally, on routes with high air traffic, contrails produced by aircraft ahead can be used to judge the situation.

Currently, many operational weather prediction models constrain their relative humidity fields to ice saturation; accordingly these models are not able to predict ice-super-saturation and production of persistent contrails. However, as the models are continuously developed, this situation will certainly change in the near future. In fact, the European Centre for Medium Range Weather Forecast (ECMWF) model uses since September 2006 a cirrus scheme, that allows for ice-super-saturation (Tompkins et al., 2007), and validated contrail forecast models also exist (Stuefer et al, 2005)

The following scenario should demonstrate the possible solution for the contrail cirrus problem: Cruising at flight level 290 the pilot is informed by the contrail detection system, that a contrail forms behind the aircraft and looking downward (s)he can see the shadow cast by the contrail on a low level cloud deck. A sheet of thin cirrus slightly above indicates higher moisture there and a short look at the air traffic and collision warning system indicates, that the next lower levels are free of air traffic. Due to the high albedo of the low-level cloud deck even during daytime a substantial radiative forcing of the contrail has to be expected. So (s)he decides to change to the next lower levels and starts the descent after a short chat with the air traffic controller, who has the same information on the display. After a descent of 800 ft the contrail (or moisture) indicator shows that the air is dry enough to avoid contrail formation. Therefore (s)he stops the descent here and continues the flight at this level. Meanwhile both, the moist layer and the descent are automatically integrated into the air traffic management system and used to assign slightly changed altitudes for the following air traffic. The moist layer is also assimilated into the atmospheric model that is used for flight planning.

Considering such a learned system it seems possible to avoid a substantial fraction of contrail production without major impact on fuel usage as only small deviations from the optimal flight altitudes are required. In addition it is possible to concentrate the effort on weather situations leading to a strong radiative forcing of contrails and contrail cirrus, which occur mainly late afternoon and at night. In regions with very dense air traffic the high density of information on supersaturated regions should allow to plan the flight altitudes according to the weather situation, whereas in regions with less information (and less air traffic) the flexible change of flight levels should be possible, as long as the airspace is controlled.

4. CONCLUSIONS

We have shown that it is possible to reduce the climate impact of contrails significantly by only small changes in flight altitude. A general shift of the whole air traffic, as it has been envisaged in various studies (e.g. Fichter et al., 2004; Noland et al., 2004) is probably not required. Necessary prerequisites for the introduction of such a system are the development towards a flexible free flight, the onboard detection of supersaturated air (a good hygrometer) or of contrails, and an assimilation system for the atmospheric state capable of handling super-saturation. All these factors are technically feasible. The most important factor is the ethical and political will to act for the mitigation of the climate impact of air traffic.

5. REFERENCES

[1] Appleman, H., 1953. The formation of exhaust condensation trails by jet aircraft. Bulletin of the American Meteorological Society. 34, 14-20.

[2] Bekebrede, G., 1999. Air transport operations and relation to emissions. Chapter 8 in: Aviation and the Global Atmosphere. IPCC Special Report, J.E. Penner et a. (Eds.), Cambridge University Press.

[3] Fichter, C., Marquart, S., Sausen, R., Lee, D.S., Norman, P.D., 2004. Impact of cruise altitude on contrails. In: Sausen, R., C. Fichter, and G. Amanatidis (Eds.), 2004: Aviation, Atmosphere and Climate (AAC). Proceedings of a European Conference, Friedrichshafen, Germany, 30 June to 3 July 2003. European Commission, Air pollution research report 83, ISBN 92-894-5434-2. 322-327.

[4] Gierens, K., Kohlhepp, R., Spichtinger, P., Schroedter-Homscheidt, M., 2004. Ice supersaturation as seen from TOVS. Atmospheric Chemistry and Physics. 4, 539-547.

[5] Helten, M., Smit, H.G.J., Sträter, W., Kley, D., Nedelec, P., Zöger, M., Busen, R.,1998. Calibration and performance of an automatic compact instrumentation for the measurement of relative humidity from passenger aircraft. Journal of Geophysical Research. 103, 25643-25652.

[6] Intergovernmental Panel on Climate Change, 1999. Aviation and the Global Atmophere. A special Report of IPCC Working Groups I and III. Cambridge University Press Cambridge

[7] Leiterer, U., Dier, H., Naebert, T., 1997. Improvements in radiosonde humidity profiles using RS80/RS90 radiosondes of Vaisala. Contributions to Atmospheric Physics 70, 319 - 336.

[8] Mannstein, H., Schumann, U., 2005 Aircraft induced contrail cirrus over Europe, *Meteorologische Zeitschrift* 14 (4), pp. 549-554

[9] Meerkötter, R., Schumann, U., Doelling, D.R., Minnis, P., Nakajima, T., Tsushima, Y., 1999. Radiative Forcing by Contrails. Annales Geophysicae 17, 1080-1094.

[10] Mulkerin, T., 2003. Free flight is in the future: Large-scale controller pilot data link, communications testbed. IEEE Aerospace and Electronic Systems Magazine (0885-8985), vol. 18, No 9, 23-27.

[11] Noland, R.B., Williams, V., Toumi, R., 2004. Policies for mitigating contrail formation from aircraft. In: Sausen, R., C. Fichter, and G. Amanatidis (Eds.), 2004: Aviation, Atmosphere and Climate (AAC). Proceedings of a European Conference, Friedrichshafen, Germany, 30 June to 3 July 2003. European Commission, Air pollution research report 83, ISBN 92-894-5434-2. 328-333.

[12] Sausen, R., Gierens, K., Ponater, M., Schumann, U., 1998. A diagnostic study of the global distribution of contrails. Part I: Present day climate. Theoretical and Applied Climatology 61, 127-141.

[13] Sausen, R., Fichter, C., Amanatidis G., (Eds.), 2004. Aviation, Atmosphere and Climate (AAC). Proceedings of a European Conference, Friedrichshafen, Germany, 30 June to 3 July 2003. European Commission, Air pollution research report 83, ISBN 92-894-5434-2.

[14] Schmidt, E., 1941: Die Entstehung von Eisnebel aus den Auspuffgasen von Flugmotoren. Schriften der Deutschen Akademie für Luftfahrtforschung 44, 1-15.

[15] Schumann, U., 1996: On conditions for contrail formation from aircraft exhausts. Meteorologische Zeitschrift 5, 4 - 23.

[16] Schumann, U., Busen, R., Plohr, M., 2000. Experimental test of the influence of propulsion efficiency on contrail formation, Journal of Aircraft 37, 1083-1087.

[17] Spichtinger, P., Gierens, K., Leiterer, U., Dier, H., 2003. Ice supersaturation in the tropopause region over Lindenberg, Germany. Meteorologische Zeitschrift 12, 143 - 156.

[18] Stuefer, M., Meng, X., Wendler, G., 2005: MM5 contrail forecasting in Alaska, *Monthly Weather Review* 133 (12), pp. 3517-3526

[19] Tompkins, Adrian M.; Gierens, Klaus; Rädel, Gaby 2007: Ice supersaturation in the ECMWF integrated forecast system. Quarterly Journal of the Royal Meteorological Society, 133, P. 53 - 63, DOI 10.1002/qj.14

[20] Williams, V, Noland, R.B., Toumi, R., 2002: Reducing the climate change impacts of aviation by restricting cruise altitudes, Transportation Research Part D: Transport and Environment, Volume 7, Issue 6, Pages 451-464.