P8.13 CONTRAIL STUDIES AND FORECASTS IN THE SUBARCTIC ATMOSPHERE ABOVE FAIRBANKS, ALASKA

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1. INTRODUCTION

Contrails are of interest for scientists investigating atmospheric radiation transfer processes, the chemical state of the atmosphere, and their potential for climatic change (IPCC 1999). Due to the composition of ice crystals, the radiative characteristics of contrails are similar to those of thin layers of naturally occurring cirrus clouds. Meerkoetter et al. (1999) pointed out the effect of contrails to reduce daily amplitudes of temperatures in the lower atmosphere by reducing the net radiation to the surface during the day and reducing the infrared losses from the surface during the night. For quantification efforts of the radiative forcing it is necessary to estimate the persistence of contrails, which may range from a few seconds to several hours. Due to uncertainties in different remote sensing techniques for contrail detection, Minnis et al. (2003) point out the need of ground based observations of contrails. Ground based observations are also one of the main tools for tuning and validation of theoretical contrail- coverage models (Duda et. al 2002).
Schmidt (1941) and Appleman (1953) described originally contrail formation criteria. By considering the entrainment of the heated and moist exhaust gas to the ambient air, a 'critical' temperature is calculated as the threshold temperature to determine if saturation occurs; contrails are expected to form for critical temperatures higher than the wake- ambient air- temperatures. To detect a contrail visibly, a minimum ice crystal content is necessary. Contrail registration and highly accurate measurements of temperature and humidity were carried out within the framework of the 'contrail and cloud effects special study (SUCCESS) experiment (Jensen et al. 1998); in situ measurements in the plume of a DC-8 aircraft confirmed previous assumptions that contrail formation requires saturation with respect to water. In visible contrails super-saturation with respect to water was observed, a phase change from water droplets to ice crystals might have occurred immediately.
For describing the thermodynamics of an air parcel that is influenced by the entrainment of moist and warm exhaust gases, an isobaric mixing process is assumed.
We have used the approach of Goff and Gratch (1946) for the temperature dependence of the saturation vapor pressure, $\frac{de_S}{dT}$. For the derivation of threshold temperatures for contrail formation a previously saturated environment was considered first. The stipulation for the threshold temperature $T_{crit,100}$ is defined as:

$$\frac{dr_S}{dT}(T_{crit,100}) = \frac{dr_f}{dT} = CF \quad (1)$$

where r_s denotes the saturation mixing ratio (g/kg) and dr_f accounts for the change of mixing ratio due to the water vapor produced by the engine combustion. Schumann (1996) summarized the Schmidt/Appleman theory; he considered also the propulsion efficiency of an aircraft (Busen and Schumann, 1995) in order to derive accurate contrail factors. Critical temperatures $T_{crit,h}$ for non-saturated conditions (relative humidity h <100 %) were derived according to:

$$T_{crit,h} = T_{crit,100} - \frac{(r_s\big|_{T_{crit,100}} - \frac{h}{100} r_s\big|_{T_{crit,h}})}{CF} \quad (2)$$

Equations 1 and 2 were solved iteratively in order to obtain the critical temperatures $T_{crit,100}$ *(p)* and $T_{crit,h}$ *(p, h)* for a previously estimated contrail factor *CF*.

2. DATA AND SELECTED METHODOLOGY

We have collected a comprehensive dataset for contrail formation for the subarctic atmosphere overhead Fairbanks. The observational methods included direct visual observations and continuous all sky digital camera imagery (Wendler and Stuefer, 2002). Visual observations were especially required for a definite classification of 'no-contrail' cases and over-flights, when an aircraft formed a contrail, which dissolved within a few seconds. As contrails often dissipate into faint contrail- patches until they reach an invisible state, persistence interpretation from different observations may vary. We had 4 observers, who did visual sky inspection at times of aircraft passages for this study; the lead author of this paper conducted 90 % of the observations ensuring homogeneity of the data.
The analysis of the persistence of longer lasting visible contrails was supported by a digital camera, which was directed to the zenith and equipped with a 180 degrees fish-eye lens. We used a commercial Canon Powershot G2 camera situated below a highly transparent dome on the roof of the Geophysical Institute of the University of

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Alaska in Fairbanks. Due to the optics of the lenses resulting in strong distortion of the images at the margins, analysis of aircrafts were restricted to a wide-angle region of about 140 degrees. In order to obtain enough image details, we had chosen a resolution of 72 ppi resulting in a size of 1600x1200 pixels for the 32bit color- coded images. The temporal spacing between successive images was 1 minute. Aircrafts flying directly overhead at a standard altitude of 29000 feet were captured along a distance of about 50 kilometers; typically 2 to 3 successive images displayed these over-flights. In few cases the camera images showed persistent contrails for time periods up to several hours; these contrails were formed at altitudes and during situations of weak wind-drift. Except for some of the persistent long- lasting contrails the observers confirmed all of the contrails/no-contrails included in our database. Sometimes the picture's resolution was high enough to recognize an airplane even when it was not forming a contrail, but for many cases the contrast between a faint dissipating contrail and the background-sky was too low resulting in a lower estimation of the lifetime than using visual inspection. Nevertheless the dome camera was essential for comparison purpose ensuring homogeneity of observations.

Flight information data for commercial airplanes were derived from Federal Aviation Administration (FAA) flight data (Flyte Trax 2002 Version 2.5) software; flight traffic information, which was updated every minute, was available to the ground- observer directly due to an online network connection to the FAA. The tracking of commercial flights in near real time alerted the observer in case of aircraft passages overhead Fairbanks. Only daytime aircraft passages and aircrafts flying under cruise condition, within 50 kilometers of Fairbanks and above 15000 feet were considered. Observations were mostly restricted to days with predominant clear skies or few clouds overhead. Several contrails have been observed below overcast skies, between clouds or during darkness; these situations do not favor accurate observations of the contrails persistence and were omitted in our database.

From March 2000 to March 2004, 704 over-flights were recorded. The most frequently observed airplane types were Boeing 747-200 and Boeing 747-400, together comprising 65% of all observations. Cruising altitudes varied from flight-level 210 (6,400 m) to flight-level 450 (13,716 m). The most frequent direction of the flights was towards the West (33.5%) with destination airports in Japan; 29.9% of the aircrafts originated in Anchorage and flew north to Europe via the polar route. Nearly 20% of all flights came from Europe going south to Anchorage, while all other directions were less frequent.

The majority of commercial planes overhead Fairbanks formed contrails, therefore we had a biased database including significant more contrail observations than no-contrail observations. 'No- contrails' refer to cases when an aircraft has been spotted while not forming a contrail; these cases require excellent visibility. A total of 608 contrails were confirmed, ranging from threshold contrails, which dissolved within a few seconds, to long lasting contrails, which could be seen in some cases for several hours. For comparison purpose we classified empirically 3 different types according to the lifetime: the short duration (threshold) contrails with a lifetime less or equal to 1 minute, the medium duration contrails lasting between 1 and 10 minutes and the long duration contrails persistent longer than 10 minutes.

Frequently we observed several aircrafts within short time periods on one day; some aircraft- type characteristics could be observed from aircrafts often cruising at same altitudes. Some cases of different contrail characteristics were derived from successive aircrafts of same type, which passed at different altitudes.

National Weather Service (NWS) radiosonde measurements were available at Fairbanks Airport twice daily at nominal 00:00 h and 12:00 h GMT. We used these data as input for the contrail algorithm. The available full- resolution data include temperature, humidity and wind parameters at mandatory and intermediate measurement levels of the sounding. When assigning meteorological sounding data to aircraft observations, errors might occur due to a time lag between the sounding and the observation. We therefore restricted our database to aircraft passages only, which occurred within 2 hours to the radiosonde measurements, and used the corresponding sounding data. From the total number of 704 observations 377 observations occurred within 2 hours to the soundings, which were classified into 168 short, 61 medium and 93 long persisting contrails. A number of 55 aircrafts were spotted while not forming a contrail. From the corresponding sounding data-tables we looked for the 2 adjacent sounding levels to the aircraft altitude and interpolated the atmospheric parameters. The pressure (p) was interpolated under the assumption $z \sim ln(p)$ using the barometric height equation, where z is the altitude of the aircraft; temperature and dew-point temperature were interpolated linearly.

Errors might occur due to a dry bias in humidity measurements with decreasing temperatures with the used Vaisala- radiosondes. A little sensitivity of critical temperatures $T_{crit,h}$ to ambient relative humidity values less than 70% was derived (Stuefer et al., submitted 2004), however errors of more than 1ºC in the calculation of $T_{crit,h}$ might occur at high relative humidity (h>70%). Humidity correction factors up to 2.4 at –70ºC were derived for Vaisala RS80-A radiosondes (Milosevich et al. 2001). In Fairbanks NWS uses Vaisala RS80-57H radiosondes; unfortunately no correction factors for humidity are available for this study. We therefore used as a first assessment radiosonde humidity measurements without correction.

3. RESULTS AND DISCUSSION

Due to the low subarctic tropopause altitude of typically 10,000 m overhead Fairbanks, about 35% of the over-flights occured in the lower stratosphere with reduced vertical atmospheric- mixing processes when compared to the troposphere. Statistics of atmospheric parameters at the flight levels derived from atmospheric soundings revealed partly significant differences for the no-contrail and contrail cases. The temperatures at aircraft altitudes ranged from -32ºC to -70ºC (*Fig. 1*). Almost all contrail observations occurred at altitudes with temperatures below -45ºC. The best separation for the occurrence of contrails is –50.5ºC; above this temperature 82% of the no-contrails occurred, whereas 91% of the contrails were observed below –50.5ºC.

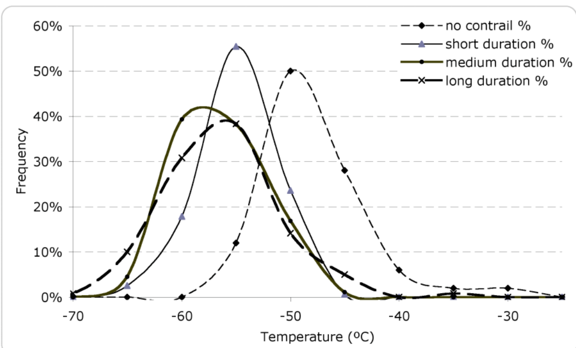

Figure 1: Temperatures at flight level for different contrail lifetimes and “no-contrail” cases at Fairbanks, Alaska, March 2000 – March 2003.

The frequency distribution of the humidity levels at aircraft altitudes shows a significant increase with the persistence of contrails. Seventy-six percent of ‘no contrails’ were observed with relative humidity values of less than 30%. In contrast, 96% of the 'long-lasting contrails’ occurred during situations with relative humidity values higher than 30%. Consequently the mixing ratio values are small for no-contrail cases, and increase with the increasing lifetime of the contrails. For example, the most frequent value for long lasting contrails is about three times as high (0.03 g kg^{-1}) as for no contrail occurrences (about 0.01g kg^{-1}). The mixing ratio deficit, defined as the difference between saturation mixing ratio and the measured mixing ratio, is also statistically significantly different between the contrail and no-contrail cases. Mixing ratio deficits of less than 0.10 g kg^{-1} were derived for 89.3 % of all contrail cases, whereas 80.0% of the no-contrails showed deficits above 0.10 g kg^{-1}.
Critical temperatures were calculated using *equation 2* for the data included in our reference database. In order to obtain appropriate contrail factors (*CF*) for the separation of contrail from no-contrail cases, we applied a wide range of contrail factors from 0.02 g $(kg\ K)^{-1}$ to 0.05 g $(kg\ K)^{-1}$ *(Fig. 2*). A hit rate of 91% for separating the occurrence and non-occurrence of contrails was derived for a contrail factor of 0.037 g $(kg\ K)^{-1}$. The restriction of our database to Boeing 747 jets resulted in a higher hit rate of 94% using a higher contrail factor of 0.0381 g $(kg\ K)^{-1}$. This higher contrail factor confirms our observations of successive aircrafts

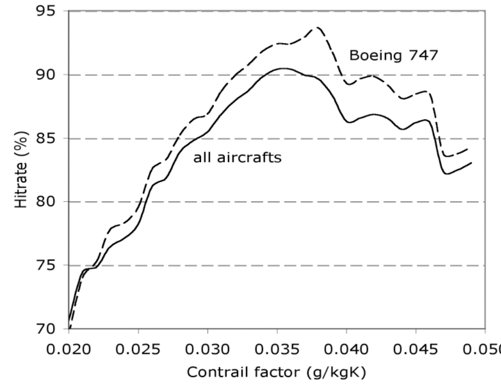

Figure 2: Validation of contrail formation algorithm using different contrail factors (CF). The dashed line shows the results for Boeing 747 jets.

at same flight levels and flight direction. Though a variety of different engines are used for the different types of Boeing 747 jets, contrails are in general more likely to form behind Boeing 747 jets than behind Boeing 777 jets.

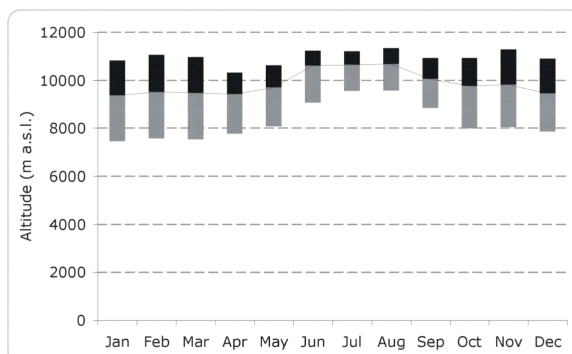

Figure 3: Tropopause height and contrail layer thickness derived from twice daily radiosonde ascents at Fairbanks Airport from January 2000 to December 2002. The layer- extents below and above the tropopause are shown in gray and black, respectively.

Using the validated contrail factors we calculated layers in the atmosphere, where contrails are likely to form. Contrail layers are mostly situated around the tropopause. In the lower stratosphere the air is already dry, and hence the likelihood of contrail formation is reduced. The height as well as the thickness of the layer varies seasonally. Figure 3 shows monthly mean contrail layers averaged over the years 2000–2002. We observed a steady decrease of the layer thickness and an increase of layer altitude from winter to summer. The altitude of the layers increases with the altitude of the tropopause; the layer extent below the tropopause is more pronounced. During the winter months the contrail layers overhead Fairbanks are almost twice as thick than during summer; the layer base altitudes are partly below 8000 m in winter.

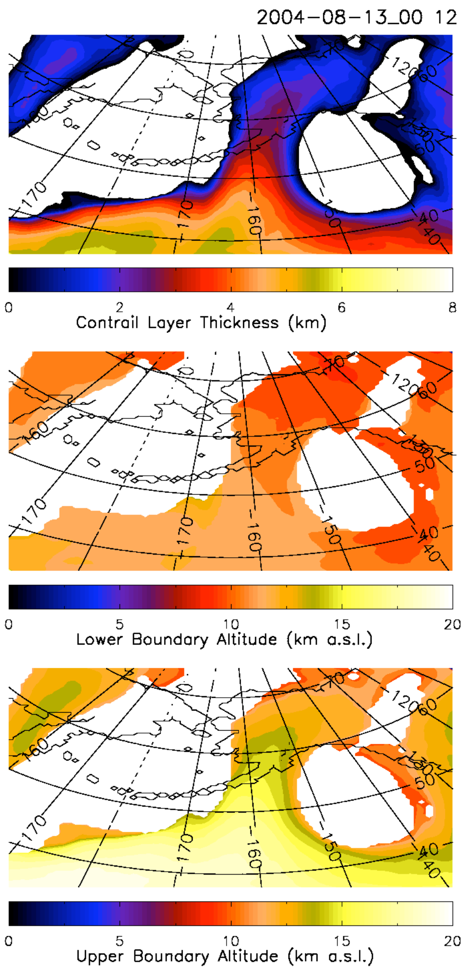

Figure 4: Map of Alaska showing a 12-hour MM5 forecast of contrail layer thickness, lower and upper layer boundary valid for 13. Aug. 2004, 12:00 h UTC.

4. FORECAST PRODUCTS

High hit rates give evidence of possible successful forecasts of contrail layers using weather forecast models. Forecasts could be involved in flight planning in order to avoid contrail formation. Airforce Weather Agency (AFWA) Mesoscale Model, Version 5 (MM5) is used for forecasting contrail layers. We developed a 'Atmospheric Contrail Layer Calculator' (ACLC) software in order to obtain operationally forecasts of areal, sectional or local contrail layer thickness and position. Forecast results have been validated locally at Fairbanks using our observations. Combined hit rates for correct forecasts of contrail occurrence higher than 82% within forecast periods of 36 hours after model initialization were derived (Stuefer et.al, submitted 2004). An example of a 12- hour forecast map for Alaska (AFWA MM5 theater number T01) is shown (*Fig. 4*). Areal contrail layer maps often show extended areas with no contrail formation-probability for higher subarctic and arctic latitudes. Actual forecasts and information is available online at http://contrail.gi.alaska.edu/.

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