A Contrail Cirrus Prediction Tool

U. Schumann*
Deutsches Zentrum für Luft- und Raumfahrt (DLR) – Institut für Physik der Atmosphäre Oberpfaffenhofen, Germany

Keywords: contrails, contrail cirrus, simulation

ABSTRACT: An new “Contrail Cirrus Prediction Tool” (CoCiP) has been developed to simulate contrail cirrus resulting from a single flight as well as from a fleet of cruising aircraft, flight by flight, regionally or globally. The method predicts contrail cirrus for given air traffic and weather prediction data. The method describes the life cycle of each contrail individually using a Lagrangian Gaussian plume model with simple bulk contrail ice properties, without feedback to meteorology. Contrails are initiated when the Schmidt-Appleman criterion is satisfied and when the ambient atmosphere is humid enough to allow for contrail persistence. The initial plume properties reflect properties of the originating aircraft. The evolution of individual contrails of cruising aircraft is computed using wind, temperature, humidity, and ice water content from numerical weather prediction (NWP) output. The plume trajectory follows horizontal and vertical wind. The model simulates shear and turbulence driven spreading, ice water content as a function of ice supersaturation, and some ice particle loss processes (turbulent mixing, aggregation and sedimentation). Radiative cloud forcing is estimated for the sum of all contrails using radiative fluxes without contrails from NWP output. The tool is kept simple to allow for efficient contrail simulations. The method has been tested for case studies with some comparisons to observations. The most critical input parameter is the NWP humidity field. The results compare favourably with observations and support interpretations of insitu, satellite and lidar observed aviation impact on cirrus clouds. CoCiP can be used to predict and minimize the climate impact of contrails.

1 INTRODUCTION

Because of the general awareness of climate change and the growth of traffic, aviation caused environmental concerns which were discussed with respect to the fleet of civil aviation since the early 1990’ (Schumann, 1994; IPCC, 1999). Despite considerable scientific progress in predicting the climate impact of aviation, still major uncertainties remain, in particular with respect to contrail cirrus (IPCC, 2007; Lee et al., 2009). The range of radiative forcing form present aviation induced contrails scatter by a factor of larger ten (from 3 to 120 W/m^2). Observed increases in cloudiness may be attributed to aviation, but the observations miss physical explanation and other explanations cannot be ruled out. Contrail and cirrus formation is a highly nonlinear process. The contrail cirrus formation depends strongly on the scale transition from the plumes with fresh soot and young contrails into spread cirrus layers. Early studies concentrated on line-shaped contrails, but contrails develop dynamically into cirrus at time scales of hours during which the line-shaped structure is lost. This scale transition requires a model that follows the history of all the contrails from the global fleet of aircraft from origin shortly after engine exit until the end of their lifetime due to sublimation or sedimentation. This paper describes a recently developed model for this purpose. The model is based on a Gaussian plume model as suggested a long time ago (Schumann and Konopka, 1994).

* *Corresponding author:* Ulrich Schumann, Deutsches Zentrum für Luft- und Raumfahrt (DLR) – Institut für Physik der Atmosphäre, D-82234 Oberpfaffenhofen, Germany. Email: ulrich.schumann @dlr.de.

2 THE MODEL

The contrail cirrus prediction (CoCiP) model is designed to analyze and predict contrail cirrus cover and the related radiative forcing from air traffic. The model simulates contrail cirrus resulting from a fleet of cruising aircraft, flight by flight, regionally or globally. The concept is illustrated by an example, see Figure 1.

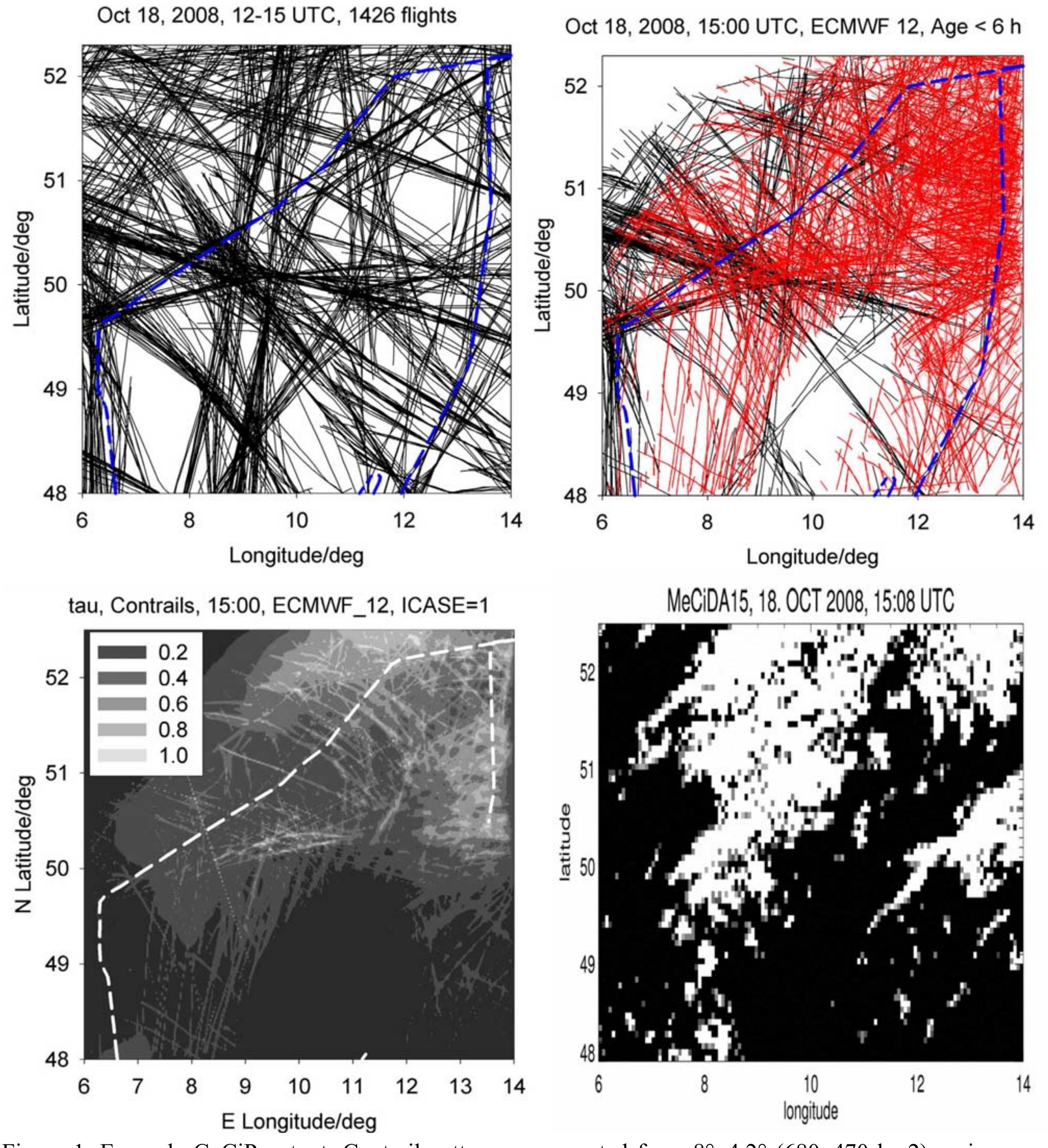

Figure 1. Example CoCiP output: Contrail pattern as computed for a 8°×4.2° (680×470 km2) region over Germany, for a case study (Oct 18, 2008, 15 UTC), for which contrails were observed visually and by lidar measurements with the Falcon research aircraft (flight path shown as blue or white dashed curve). Top left: flight paths of air traffic from all 1426 flights above 7.3 km altitude (FL 240) over Germany between 13 and 15 UTC that day. Top right: Flight segments causing contrails during recent 6 h which contribute to contrail cover at 15 UTC (black), and contrail plumes centre line (full red) together with their left and right boundaries (dashed red; closely near the centre lines). Bottom left: solar optical depth of these contrails (from CoCiP) superposed on cirrus (from ECMWF output). Bottom right: Cirrus cloud cover (white) computed by K. Graf with the MeCiDa algorithm (Krebs et al., 2007) from Meteosat data at the given time.

The method computes the contrail cirrus cover for a given time instant for given weather data and for given data of air traffic for the past covering all contrails with life times of up to six hours (in Fig 1) or about a day (for larger domains). The model requires input in terms of wind vector, temperature, humidity, and ice water content fields as available from numerical weather prediction (NWP) or climate model output, as a function of time and three dimensions (3d) in space (typical time intervals: 1-3 h; typical spatial resolution: 0.25-1 degree horizontally, 20 levels vertically from 120-500 hPa for Gemany). In addition, the model requires the irradiances for outgoing longwave radiation (OLR) and short-wave reflected radiation (RSR) at top of the atmosphere (TOA) as a function of horizontal coordinates and time. The traffic data need to be provided, flight by flight, as waypoint sequences (3 space coordinates and time) together with the aircraft type. The tool is kept simple to allow for efficient global contrail simulations. The example requires about 10 s computing time on a single processor Laptop.

The model treats each exhaust plume as a Gaussian plume (Konopka, 1995; Schumann et al., 1995; Dürbeck and Gerz, 1996). The model assumes that any mass specific concentration c in the plume has the distribution $c(x,y,z,t)= (C_0/A) \exp(-(1/2)\mathbf{x}^T\boldsymbol{\sigma}^{-1}\mathbf{x})$, where C_0 is the mass per unit length in the contrail, A is the plume cross-section area, **x** is the vector of space coordinates relative to the plume centre ($\mathbf{x}$=(x,y,z), x in flight direction, y cross-flight direction, z vertical direction), and $\boldsymbol{\sigma}(x,t)$ is the positive definite symmetric concentration-covariance matrix with matrix diagonal elements σ_{yy} and σ_{zz}, and diagonal elements $\sigma_{yz}= \sigma_{zy}$. $A = \iint \exp[-(1/2)\mathbf{x}^T\boldsymbol{\sigma}^{-1}\mathbf{x}]dy\, dz = 2\pi\, [\det(\boldsymbol{\sigma})]^{1/2}$. The initial plume has an elliptical cross-section with effective width B and depth D, $\sigma_{yy} = B^2/8$, $\sigma_{zz}=D^2/8$, so that the initial cross-section area is $A = (\pi/4)$ B D.

The model distinguishes 3 model phases: Phase 0: initial plume conditions just after engine exit; phase 1: initial plume conditions at the end of the wake vortex period (accounting for wake vortex downwash); Phase 2: plume evolution until dry-out because of ambient subsaturation or until sedimentation of the particles below the lower boundary of the computational domain (typically at 5 km altitude).

In phase 0, contrails form when the Schmidt-Appleman criterion is satisfied, i.e. when the ambient temperature T is below a critical temperature T_{LC} (Schumann, 1996) which is a function of fuel properties and the overall propulsion efficiency $\eta = (V\, F)/(m_F\, Q)$, with thrust F, true air speed V, fuel consumption per unit distance m_F and combustion heat Q, and ambient temperature T, absolute ambient humidity q, and pressure p as computed for the given time t and position **x** by bilinear interpolation in the NWP output fields. Contrails are assumed to persist when the relative humidity over ice (RHi) is larger than a critical value RHi_{crit}, which should be 100 % for good NWP input data. The ECMWF model output predicts supersaturated air masses fairly realistically (Tompkins et al., 2007). The COSMO-DE model output shows practically no supersaturation. Therefore, we run the model for this example with both input data with $RHi_{crit} = 0.9$.

The initial contrail depth is assumed to be proportional to the wake vortex maximum downwash Δz_w. This downwash is determined from a parameterization of P2P model results (Holzäpfel, 2006). The parameterization is a function of aircraft parameters (mass, speed, span width) and atmospheric parameters (Brunt Vaisaila frequency, density, and turbulent dissipation rate). The aircraft parameter values are taken from the BADA data set of EUROCONTROL.

For microphysics, we assume saturation inside the contrail plume. The initial ice water content IWC in the plume at stage 0 is set to the amount of water mass per volume in the ambient air above ice saturation. The specific water mass in the plume is the sum of ambient humidity and the amount of water emitted from the engine and mixed over the plume cross-section. During the wake vortex phase, the plume sinks and heats up adiabatically. This leads to a reduction of the saturation water mass and hence to a loss of IWC, which is computed within CoCiP accordingly.

The initial number of ice particles N per unit length is assumed to be determined by fuel consumption m_F and the soot number emission index EI_{soot}; this is consistent with recent model results (Kärcher and Yu, 2009) and the few available measurements (Schumann et al., 2002). The soot emission index is estimated according to earlier studies (Petzold et al., 1999; Eyers et al., 2005). During the wake vortex period, part of the ice particles sublimate because of the adiabatic warming and turbulent mixing with ambient air (Sussmann and Gierens, 1999). Loss factors have been computed by large eddy simulations (Kärcher et al., 2009). However, from comparisons to observed data, we got the impression that these factors are too low. Therefore we instead assume that the ratio of N in phase 1 relative to N in phase 0 is proportional to corresponding ratio of IWC.

In the evolution phase (2) of the contrails we follow the plumes in a Lagrangian manner. The plume position follows horizontal and vertical wind as analysed from the NWP data. In addition, the vertical position changes with the mean sedimentation speed of the bulk of the ice particles. We also have foreseen a rising motion component due to radiative heating. For given winds from NWP, advection is computed using a second-order Runge-Kutta scheme.

The change in plume cross-section with time as a function of vertical velocity shear S, and vertical and horizontal diffusivities D_{yy} and D_{zz} is integrated analytically (Konopka, 1995). The diffusivities are functions of plume scales, total shear S_T and stratification N_{BV} ($D_{zz}= 0.4\ w^2/N_{BV}$; w=0.1 m/s as the vertical turbulent velocity fluctuations), $D_{yy} = 0.1\ D^2\ S_T$. The shear diffusivity D_{yz} is set to zero. The shear value S (perpendicular to the plume axis) and S_T (total) are computed from differences of the corresponding wind speeds at the next available levels above and below the contrail. Since the grid spacing Δz is often large compared to the contrail depth D, we allow for an enhancement factor $f(\Delta z/D)$ (Adelfang, 1971), where $f(r) = (1/2)(1+r^m)$. The exponent m is close to 2/3 for Kolmogorov type turbulence (dependence on wavenumber k as $k^{-5/3}$) and close to 0 for 2d turbulence (k^{-3}). Here, we assume m= ½. We also have foreseen enhanced turbulent diffusivities due to radiative heating.

During integration we assume that any ice supersaturation within the air mass entrained with growing cross-section A(t) into the contrail plume gets converted to ice water content $IWC_s(t)$ immediately, leaving saturated ($RHi = RHi_{crit}$) humidity inside the contrail. Accordingly, we integrate the ice water content such that the plume ice water budget is conserved except for mixing with the humidity from ambient air. The volume mean ice particle radius r is computed locally from IWC and number N of ice particles per unit length, or n per unit volume n= N/A, so that $(4/3)\ \pi\ r^3\ n\ \rho_{ice} = IWC$ (ρ_{ice} = 917 kg/m^3 as ice bulk density). We assume that the number of ice particles remains constant unless specific particle loss processes like agglomeration or turbulent phase changes reduce the number of particles. Hence the number of ice particles follows from $dN/dt = (dN/dt)_{agg} + (dN/dt)_{turb}$. Further we use the assumptions $(dN/dt)_{agg} = -E_a\ 8\ \pi\ r^2\ V_t\ N^2/A$, and $(dN/dt)_{turb} = -E_T\ (D_{yy}/\max(D,B)^2 + D_{zz}/d_{eff}^2)\ N$, where V_t is the sedimentation velocity of particles with radius r, and $d_{eff} = A/B$, and E_a and E_T are free model parameters of order unity. These relationships are justified by dimensional analysis.

The solar optical depth τ of the contrail is computed from $\tau = 3\ Q_{ext}\ IWC\ d_{eff}/(4\ \rho_{ice}\ r_{eff})$, with extinction coefficient Q_{ext}=2 and optically effective radius $r_{eff} = C_\tau\ r$. The factor $C_\tau \cong 0.9$ depends on the particle habits and the particle size distribution function; its value is quite uncertain. The values of τ and r_{eff} form the input to a radiative forcing (RF) model which computes the RF from contrails for given OLR and RSR at TOA fit to forward calculations with libRadtran (Schumann et al., 2009).

3 APPLICATION EXAMPLES

The model has been applied to weather and traffic conditions over Germany and the North Atlantic (first global tests have also been performed) for the following case studies: 1) comparison to insitu measurements of NO_x, ice and soot particle concentrations in the contrails of six (small and large) different aircraft, at plume ages of 60 to 600 s, during the experiment CONCERT, Nov 19, 2008 (Voigt et al., 2009); 2) comparison to lidar measurements of the extinction coefficient of cirrus and contrail cirrus particles at altitudes 6-11 km along a flight path of the Falcon over Germany on Oct 18, 2008 (Schumann and Wirth, 2009); and 3) comparisons to cirrus cover and outgoing longwave radiation data obtained from Meteosat for Germany (see Fig 1) or the North Atlantic in the time period August 11-14 2005. The results show: CoCiP computes a dilution with time which agrees favourable with the NO_x measurements (Voigt et al., 2009) and with previous data (Schumann et al., 1998). The number of ice particles and soot particles computed by CoCiP compares reasonably with insitu measurements during CONCERT. The results do fit only after taking the specific aircraft properties into account. There are no indications of additional ice formation after the initial soot-controlled contrail formation. The diurnal cycle of cirrus cover and OLR computed for 3 days in the NAR shows the order of magnitude with respect to the amplitudes of cirrus cover and of OLR as derived from Meteosat (Graf et al., 2009). Also the delay time between traffic maximum and cirrus cover maximum is in the same range of 3 to 5 h as observed. Parameter studies indicate that changes of most model parameters have less than linear impact on integral results like net radiative forcing. A somewhat larger sensitivity is found for the critical relative humidity, and the parameters limiting the plume life time. The SW RF is strongly sensitive to the assumed particle habits.

For example, Figure 1 shows the 848 contrails (1069 contrail segments) that are computed to exist in the region shown at 15 UTC this day. The contrails formed from 2816 flights during the 6 h before this time. The average contrail age is 2.25 h. About 38 % of all flights (628626 flight km) in that period formed contrails. The mean fuel flow rate of contrail forming aircraft was 3.8 kg/km. The mean contrail width is 3180 m, the mean contrail length 134 km. More than 92 % of the contrails formed inside the thin cirrus, i.e. in air masses containing positive ice water content, according to ECMWF. Contrails contained 5.3×10^{11}/m ice particles per unit plume length. The mean optical depth τ was 0.054. One contrail reached $\tau = 1.1$. Not accounting for overlap of the various contrails, the cover with thin contrail cirrus would be 110 %, mostly optical thin ($\tau<0.03$). The fraction of cirrus with optical depth larger 0.4 (larger 0.05) was 4.5 % (35.5 %) without contrails and 9 % (50.6 %) with contrails, i.e. 15 % of the sky was covered with contrail cirrus of $\tau>0.05$. The contrail induced RF is 3.8 W/m^2 in the LW, -4.5 W/m^2 in the SW, and -0.64 W/m^2 net. Hence, contrails were cooling in this case. The computed contrail cover agrees - not ideally but qualitatively - with the cirrus cover derived from Meteosat (see Fig. 1). The remaining differences are mainly because of deviations of the computed RHi from the NWP data compared to reality. Best performance was obtained with ECMWF forecasts from 12 UTC that day.

4 CONCLUSIONS

A new Contrail Cirrus Prediction Tool (CoCiP) has been developed to simulate and predict contrail cirrus from a fleet of aircraft, flight by flight, regionally or globally. The model has been developed in the last year and parts are still under development. So far, the model has been tested in parameter studies in comparison with insitu, lidar, and satellite data. The most critical parameters concern the NWP humidity and the life time of contrails (sedimentation, turbulent particle loss). The results indicate that most contrails occur inside thin cirrus in the upper troposphere. The radiative forcing by contrail cirrus is far larger than estimated from line shaped contrails and may be negative at least regionally. Contrail climate impact can be reduced by proper air traffic management. The model will next be used for global evaluation of contrail cirrus RF. We plan to run it for several years and compare it with Meteosat observations. Moreover we plan for tests with research aircraft (HALO and Falcon) in a cirrus experiment “ML-CIRRUS”. The model will also be applied within the project UFO (Mannstein and al., 2009). In the future, the model may be coupled to other global models (with aerosols & chemistry) to assess the total aviation climate impact. For example it may be used to study renucleation effects from contrail-processed soot emissions. The model may be extended with plume chemistry to compute the effective chemical emissions. Higher order microphysics cloud physics may be included. The same principle approach may be used to simulate ship trails.

5 ACKNOWLEDGMENTS

The author gratefully acknowledges contributions from coworkers, in particular: K. Graf, B. Mayer, H. Mannstein, U. Hamann, R. Meerkötter (help with Meteosat, MeCiDa, LibRadTran), M. Wirth, S. Rahm (lidar), C. Voigt, T. Jurkat, H. Schlager et al. (CONCERT), F. Holzäpfel (P2P model), A. Dörnbrack, C. Keil, J. Dahl, and A. Tafferner (for access to NWP data), and K. Gierens, I. Sölch, and S. Unterstraßer (modelling). Moreover, important meteorological data and air traffic data were provided by DWD, ECMWF, DFS, and EUROCONTROL. This research is part of the DLR-project “Climate-compatible Air Transport System” (CATS).

REFERENCES

Adelfang, S. I., 1971: On the relations between wind shears over various altitude intervals. *J. Appl. Meteorol.*, ***10***, 156-159.

Dürbeck, T. and T. Gerz, 1996: Dispersion of aircraft exhausts in the free atmosphere. *J. Geophys. Res.*, ***101***, 26007-26015.

Eyers, C. J., D. Addleton, K. Atkinson, et al., 2005: AERO2k Global Aviation Emissions Inventories for 2002 and 2025.

Graf, K., H. Mannstein, B. Mayer, and U. Schumann, 2009: Aviation fingerprint in diurnal cycle of cirrus over the North Atlantic. *Intern. Conf. on Transport, Atmosphere and Climate*, Aachen and Maastricht, EUR, this volume.

Holzäpfel, F., 2006: Probabilistic Two-Phase Aircraft Wake-Vortex Model: Further Development and Assessment. *J. Aircraft*, *43*, 700-708.

IPCC, 1999: *Aviation and the Global Atmosphere*. Cambridge Univ. Press, 373 pp.

IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge Univ. Press, 996 pp.

Kärcher, B., U. Burkhardt, S. Unterstrasser, and P. Minnis, 2009: Factors controlling contrail cirrus optical depth. *Atmos. Chem. Phys.*, *9*, 6229-6254.

Kärcher, B. and F. Yu, 2009: Role of aircraft soot emissions in contrail formation. *Geophys. Res. Lett.*, *36*, L01804.

Konopka, P., 1995: Analytical Gaussian solutions for aniosotropic diffusion in a linear shear flow. *J. Non-Equilib. Thermodyn.*, *20*, 78-91.

Krebs, W., H. Mannstein, L. Bugliaro, and B. Mayer, 2007: Technical note: A new day- and night-time Meteosat Second Generation Cirrus Detection Algorithm MeCiDA. *Atmos. Chem. Phys.*, *7*, 6145-6159.

Lee, D. S., G. Pitari, V. Grewe, et al., 2009: Transport impacts on atmosphere and climate: Aviation. *Atmos. Env.*, 1–57.

Mannstein, H. and al., 2009: Smart aircraft routing – a possibility for mitigation? *Intern. Conf. on Transport, Atmosphere and Climate*, Sausen, Ed., EUR.

Petzold, A., A. Döpelheuer, C. A. Brock, and F. Schröder, 1999: In situ observation and model calculations of black carbon emission by aircraft at cruise altitude. *J. Geophys. Res.*, *104*, 22171-22181.

Schumann, U., 1994: On the effect of emissions from aircraft engines on the state of the atmosphere. *Ann. Geophysicae*, *12*, 365-384.

Schumann, U., 1996: On conditions for contrail formation from aircraft exhausts. *Meteorol. Z.*, *5*, 4-23.

Schumann, U., F. Arnold, R. Busen, J. Curtius, B. Kärcher, J. Curtius, A. Petzold, H. Schlager, F. Schröder, and K. H. Wohlfrom, 2002: Influence of fuel sulfur on the composition of aircraft exhaust plumes: The experiments SULFUR 1-7. *J. Geophys. Res.*, *107*, AAC 2-1 - AAC 2-27.

Schumann, U. and P. Konopka, 1994: A simple estimate of the concentration field in a flight corridor. *Impact of Emissions from Aircraft and Spacecraft upon the Atmosphere. Proc. of an Intern. Sci. Colloquium, Köln (Cologne), Germany, April 18-20, 1994*, Schumann and Wurzel, Eds., DLR-Mitt. 94-06, 354-359.

Schumann, U., P. Konopka, R. Baumann, R. Busen, T. Gerz, H. Schlager, P. Schulte, and H. Volkert, 1995: Estimate of diffusion parameters of aircraft exhaust plumes near the tropopause from nitric oxide and turbulence measurements. *J. Geophys. Res.*, *100*, 14147-14162.

Schumann, U., B. Mayer, K. Graf, H. Mannstein, and R. Meerkötter, 2009: A parametric radiative forcing model for cirrus and contrail cirrus. *ESA Atmospheric Science Conference, Special Publication SP-676 (6 pages)*, Barcelona, Spain, 7-11 September 2009, 1-6.

Schumann, U., H. Schlager, F. Arnold, R. Baumann, P. Haschberger, and O. Klemm, 1998: Dilution of Aircraft Exhaust Plumes at Cruise Altitudes. *Atmos. Env.*, *32*, 3097 - 3103.

Schumann, U. and M. Wirth, 2009: Optical depth of cirrus and embedded contrails from airborne Lidar and models *Geophysical Research Abstracts, EGU2009-5128*, *11*, 1.

Sussmann, R. and K. Gierens, 1999: Lidar and numerical studies on the different evolution of vortex pair and secondary wake in young contrails. *J. Geophys. Res.* , *104*, 2131-2142.

Tompkins, A., K. Gierens, and G. Rädel, 2007: Ice supersaturation in the ECMWF Integrated Forecast System. *Q. J. R. Meteorol. Soc.*, *133*, 53–63.

Voigt, C., U. Schumann, T. Jurkat, and al., 2009: Detection of young contrails – selected results from the CONCERT (CONtrail and Cirrus ExpeRimenT) campaign. *Intern. Conf. on Transport, Atmosphere and Climate*, Aachen and Maastricht, EUR, this volume.