The lifecycle and climate-impact of contrail cirrus

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Contrail properties simulated with CoCiP, coupled to CAM or ECMWF
Results show reasonable agreement with observations
Questions:
• what determines the life cycle of a contrail?
• what determines climate impact of contrails?
Contrail Cirrus Simulation and Prediction Model (CoCiP)

**Input:**
- Aircraft, emission (BADA)
- Traffic, e.g., FAA-ACCRI
- Meteorology from, e.g., CAM, ECMWF

**Contrail formation (SAC) with ice**
\[ \text{Contrail formation} = f(m_p, PE_{\text{soot}}) \]

Lagrangian contrail segment (mixing, advection, sedimentation)

Here: persistent contrail positions

**Output:**
- Contrail life cycle, cover, \( \tau \), RF, EF, ...
- Cirrus
- Simulation (insitu, Lidar, MSG, Modis)
- Sensitivity studies
- Prediction & Mitigation
- Global or Regional

Schumann (GMD, 2012), Schumann et al. (JAMC, 2012), Schumann and Graf (JGR, 2013), Jeßberger et al. (2013), Schumann, Penner et al. (ACP, 2015), Voigt et al. (2016)
Radiative forcing (RF)
Shortwave (SW), longwave (LW), dehydration, net

U. Schumann: Contrail Cirrus

Schumann et al. (2015)
Burkhardt and Kärcher (2011)
Schumann and Graf (2013)

CoCiP ECMWF offline

CoCiP CAM3/IMPACT online

net = SW + LW

ECHAM4 - CCMOD

RF (mW/m²)

0 50 100

180 150W 120W 90W 60W 30W 0 30E 60E 90E 120E 150E 180

W m⁻²

180 150W 120W 90W 60W 30W 0 30E 60E 90E 120E 150E 180

b)
Observed and simulated contrail properties

Model (CoCiP+CAM):
Data from Schumann, Penner et al. (2015)
White curves with grey shading: 0, 10, 50, 90, 100% percentiles

In-situ measurements:

Remote sensing observations:

Remote sensing of life cycle:
(Meteosat, ACTA, Vazquez-Navarro et al., 2015), percentiles of optical depth data.

(Schumann and Heymsfield, 2016, AMS Monogr.; submitted)
Contrail ages

observed (ACTA, Vazquez and Navarro et al., ACP, 2015)

and simulated (CoCiP)

Most contrails, even when persistent, remain short-lived

a few get old (up to 36 h) as observed.

U. Schumann: Contrail Cirrus
What determines the lifetime of contrails?

Contrail lifetime depends on:
- initial number of ice particles
- ambient RHi, T, p
- mixing and sedimentation
- ambient vertical motion incl. waves
- particle losses in sinking wake vortex

Number of ice particles in young contrail determined mainly by:
- emissions and wake dynamics
- number of soot particles
- ambient RHi, p, Temperature

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\[ V_f = f(r) \]
What determines the climate impact of contrails?

Energy Forcing (EF), Radiative Forcing (RF) and their dependence on Air Traffic Density (ATD) and lifetime

\[ EF \equiv \int \frac{W}{\text{lifetime}} RF' \, dt \]

\[ RF = \frac{\int_{\text{flight distances}} EF \, ds}{\Delta t \cdot \text{year} \cdot 4\pi R^2_{\text{Earth}}} = EF_{\text{mean}} \cdot \text{ATD} \]

\[ EF \approx \frac{dRF'}{d\tau} \int \frac{W}{\text{lifetime}} \tau \, dt \]

Key:
- W: contrail width
- \( \tau \): optical depth; W \( \tau \): total extinction
- lifetime: maximum contrail age
- RF': local RF for 100% cover, \( RF'_{\text{LW}} + RF'_{\text{SW}} \)
- ATD = Air traffic density = flight distance/(area*time)
- RH_i, controls contrail occurrence
Total extinction = width × optical depth: $W\tau$

$$W\tau = \left[ \frac{9\pi}{16 \rho_{\text{ice}}^2} \right]^{1/3} C Q_{\text{ext}} m_F \left[ f_s f_c PEI_{\text{soot}} \right]^{1/3} \left[ EI_{H_2O} + \frac{(RHi - 1)N_{\text{dil}} M_{H_2O} P_{\text{ice}}(T)}{N_{\text{air}} P} \right]^{2/3}$$

Linear in fuel consumption $m_F$ ($\sim$ aircraft size)

1/3 power of $PEI_{\text{soot}}$
2/3 power of $RHi$
2/3 power of dilution $N_{\text{dil}}(t)$

Jeßberger et al. (ACP, 2013)
Dilution in contrails, stronger than for passive tracers and strongly enhanced by sedimentation ($V_T =$ terminal fall velocity)

$$N_{dil}(t) = a t^\alpha$$

in contrails: $\alpha \approx 1.28$

passive tracers:
$$N_{dil} = 7000 (t / t_0)^{0.8}$$

$V_T < 0.016 \text{ m s}^{-1}$
$V_T > 0.016 \text{ m s}^{-1}$

$\alpha = 1.28$
Energy Forcing: time integral of $W\tau$

$$EF = \frac{dRF^a}{d\tau} \left[ \frac{9\pi}{16\rho_{ice}^2} \right]^{1/3} C Q_{ext} m_F \left[ f_s f_c \right] \left[ PEI_{soot} \right]^{1/3} \left[ \frac{(RHi - 1) M_{H_2O} P_{ice} (T)}{M_{air} p} \right]^{2/3} \frac{a}{1 + 2\alpha / 3} \left( \text{lifetime} \right)^{1 + 2\alpha / 3}$$

Increase with age $^{**}(1.65 \pm 0.2)$
Which contrails cause largest age and climate impact (EF)

- weakly supersaturated air
Implication:
RF: sensitive to soot number emissions

soot number reduction gets more important when contrail ice sedimentation occurs often

ECHAM from Bock and Burkhardt (TAC, 2015)
Conclusions

- There are externally and internally limited contrails
- Most contrails are internally limited (often by sedimentation)
- The climate impact (EF) increases with power $1.65 \pm 0.2$ (nearly quadratic) with age
- Largest age for weak ice supersaturation, low vertical velocity, at low temperatures, near the tropopause

Further info in: Schumann and Heymsfield (2016) submitted