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?

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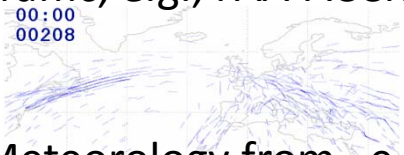
Contrail Cirrus Simulation and Prediction Model (CoCiP)

Input:

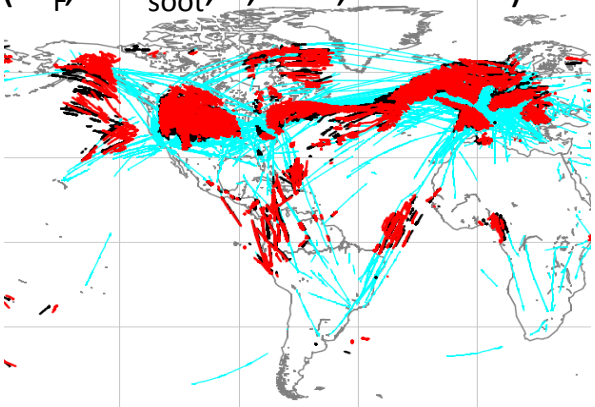
Aircraft, emission (BADA)

Traffic, e.g., FAA-ACCRI



Meteorology from , e.g., CAM, ECMWF

Contrail formation (SAC) with ice =f(m_F, PEI_{soot}, T, RHi, dilution)



Lagrangian contrail segment (mixing, advection, sedimentation)

Here: persistent contrail positions

Output:

Contrail life cycle, cover, τ, RF, EF,...

Cirrus

Simulation (insitu, Lidar, MSG, Modis)

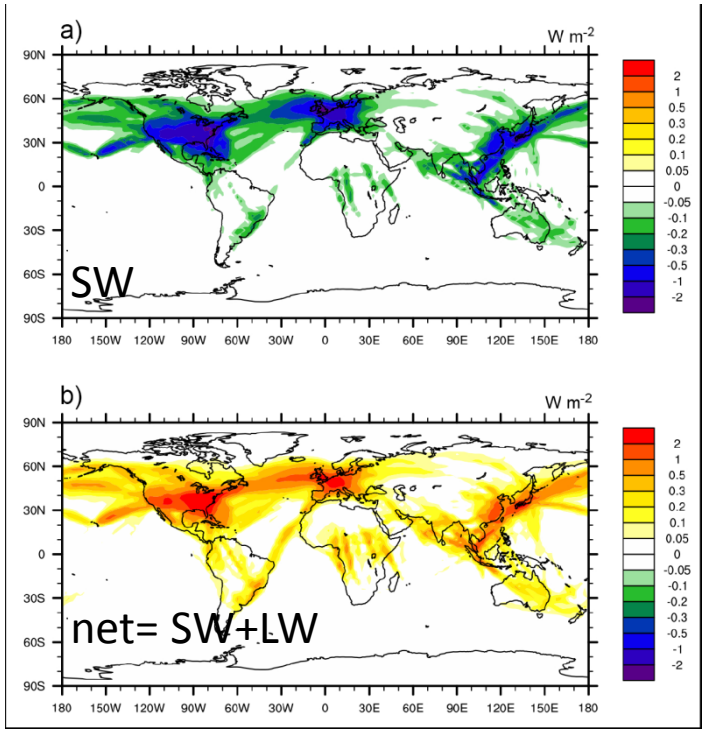
Sensitivity studies

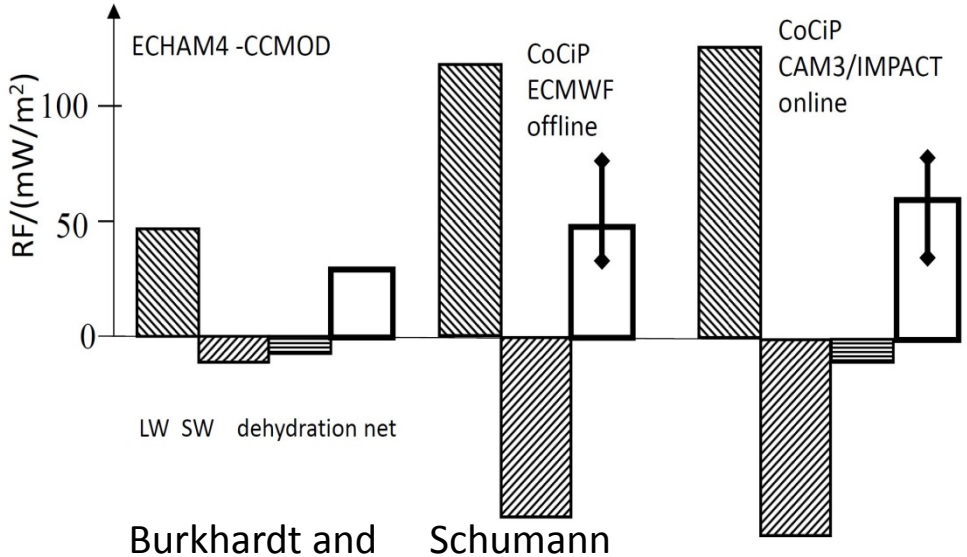
Prediction & Mitigation

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





Burkhardt and Kärcher (2011)

Schumann and Graf (2013)

Schumann et al. (2015)

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:

Knollenberg 1972; Baumgardner and Cooper 1994; Poellot et al. 1999; Schröder et al. 2000; Gao et al. 2006; Febvre et al. 2009; Heymsfield et al. 2010; Voigt et al. 2011; Jones et al. 2012; Jeßberger et al. 2013; Schumann et al. 2013a; Kaufmann et al. 2014.

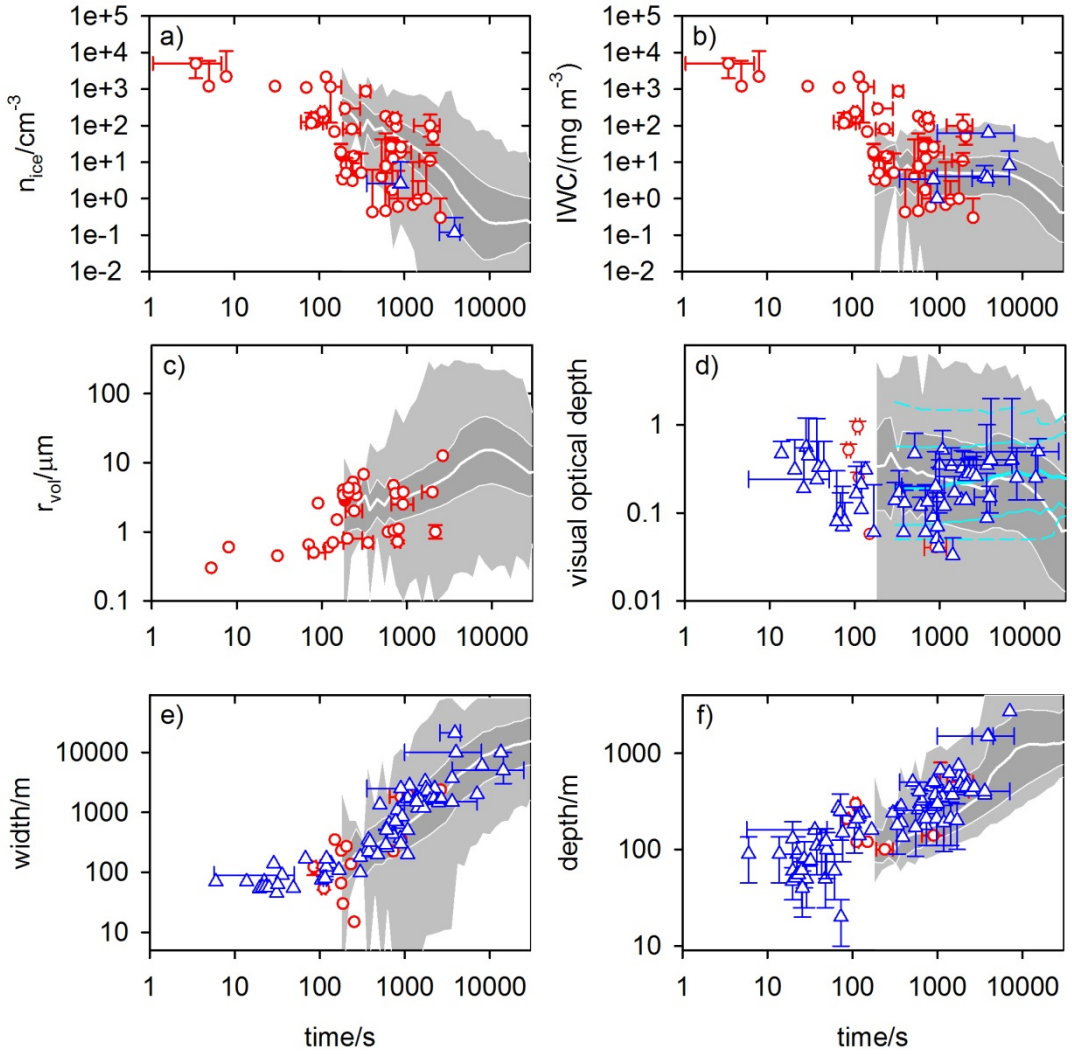
Remote sensing observations:

Hoshizaki et al. 1975; Baumann et al. 1993; Freudenthaler et al. 1995, 1996; Minnis et al. 1998; Spinhirne et al. 1998; Sussmann and Gierens 1999; Duda et al. 2004; Atlas et al. 2006; Atlas and Wang 2010; Schumann et al. 2013b.

Remote sensing of life cycle:

(Meteosat, ACTA, Vazquez-Navarro et al., 2015), _percentiles of optical depth data .

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



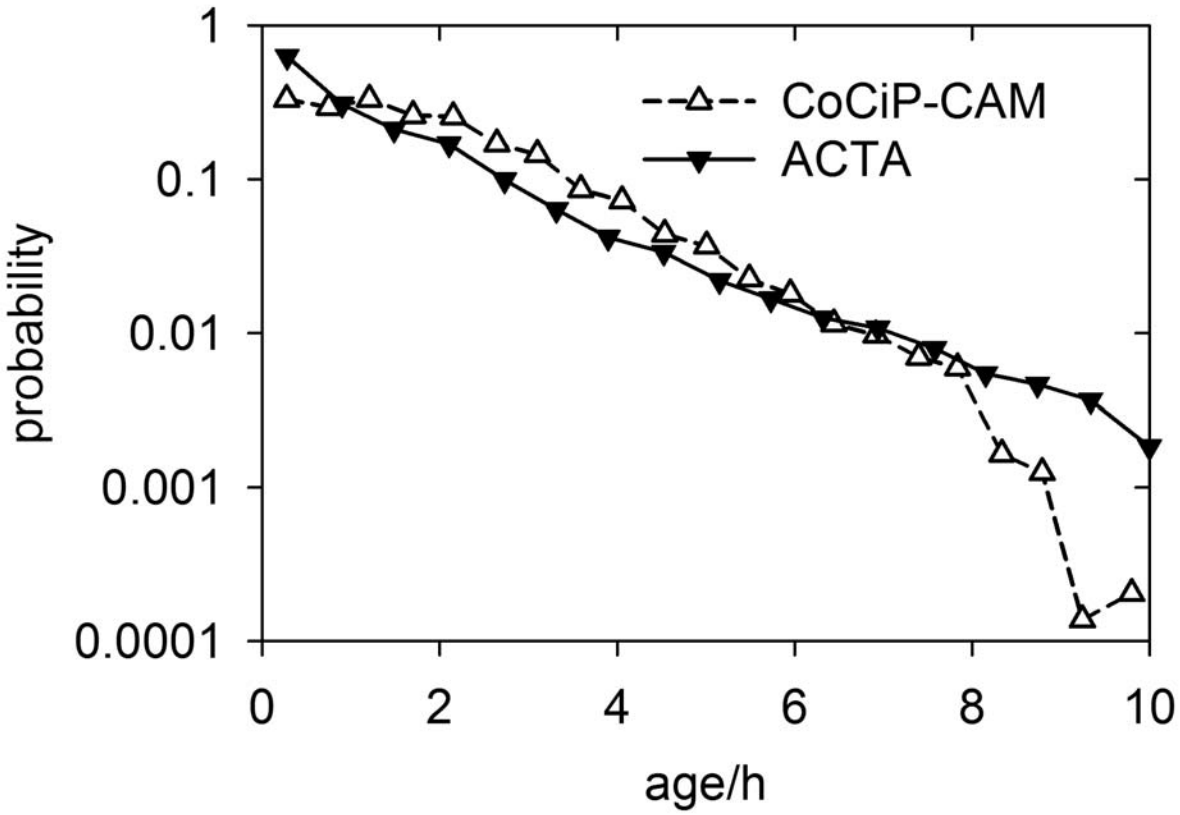
Contrail ages

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

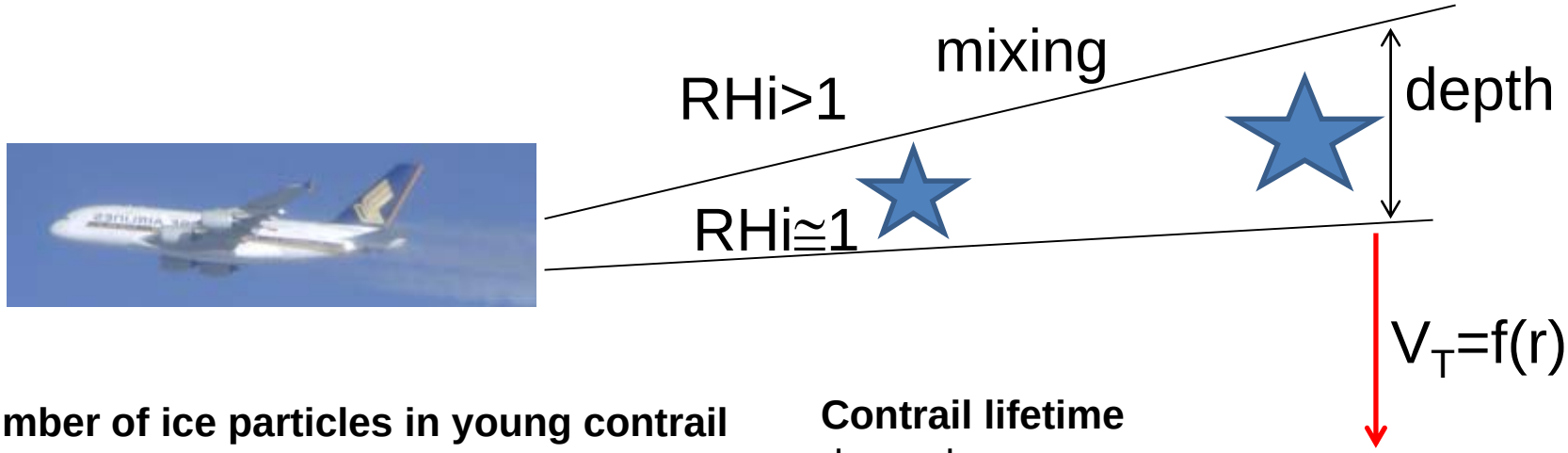
and simulated (CoCiP)

Most contrails, even when persistent,
remain short-lived

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



What determines the lifetime of contrails



Number of ice particles in young contrail
determined mainly by

- emissions and wake dynamics
- number of soot particles
- ambient RHi, p, Temperature
- particle losses in sinking wake vortex

Contrail lifetime
depends on

- initial number of ice particles
- ambient RHi, T, p
- mixing and sedimentation
- ambient vertical motion incl. waves

externally/internally limited contrail lifecycles

What determines the climate impact of contrails?

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

$$EF \equiv \int_{lifetime} W\, RF'\, dt$$

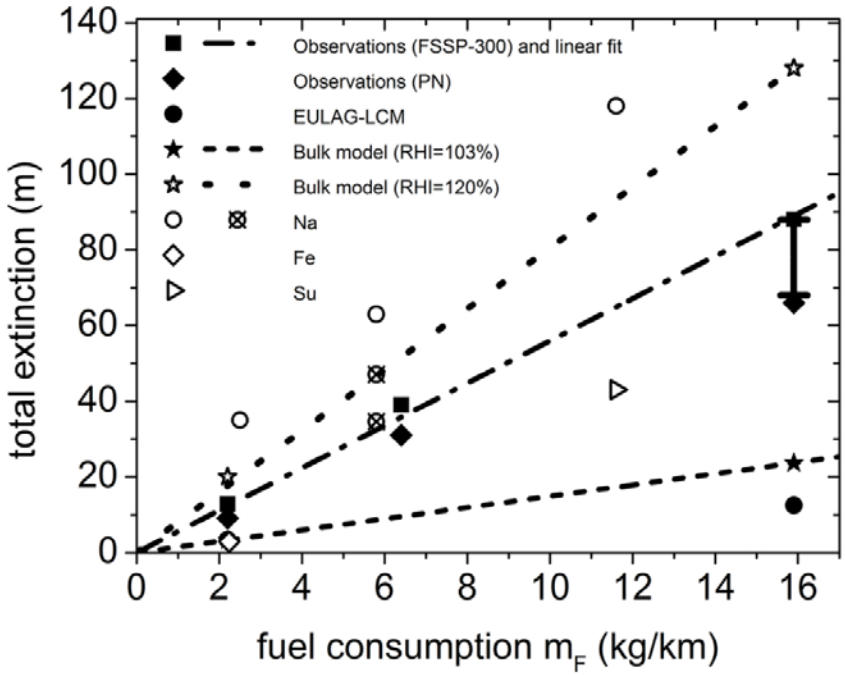
$$RF = \frac{\int_{flight\ distances} EF\, ds}{\Delta t_{year}\, 4\pi R_{Earth}^2} = EF_{mean}\, ATD$$

$$EF \approx \frac{dRF'}{d\tau} \int_{lifetime} W \tau\, dt$$

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

Total extinction = width × optical depth: Wτ

$$W\tau = \left[\frac{9\pi}{16\rho_{ice}^2}\right]^{1/3} C Q_{ext} m_F \left[f_s f_c PEI_{soot}\right]^{1/3} \left[EI_{H2O} + \frac{(RHi-1) N_{dil} M_{H2O} p_{ice}(T)}{M_{air}\, p}\right]^{2/3}$$



linear in fuel consumption m_F
(~ aircraft size)

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

Jeßberger et al. (ACP, 2013)

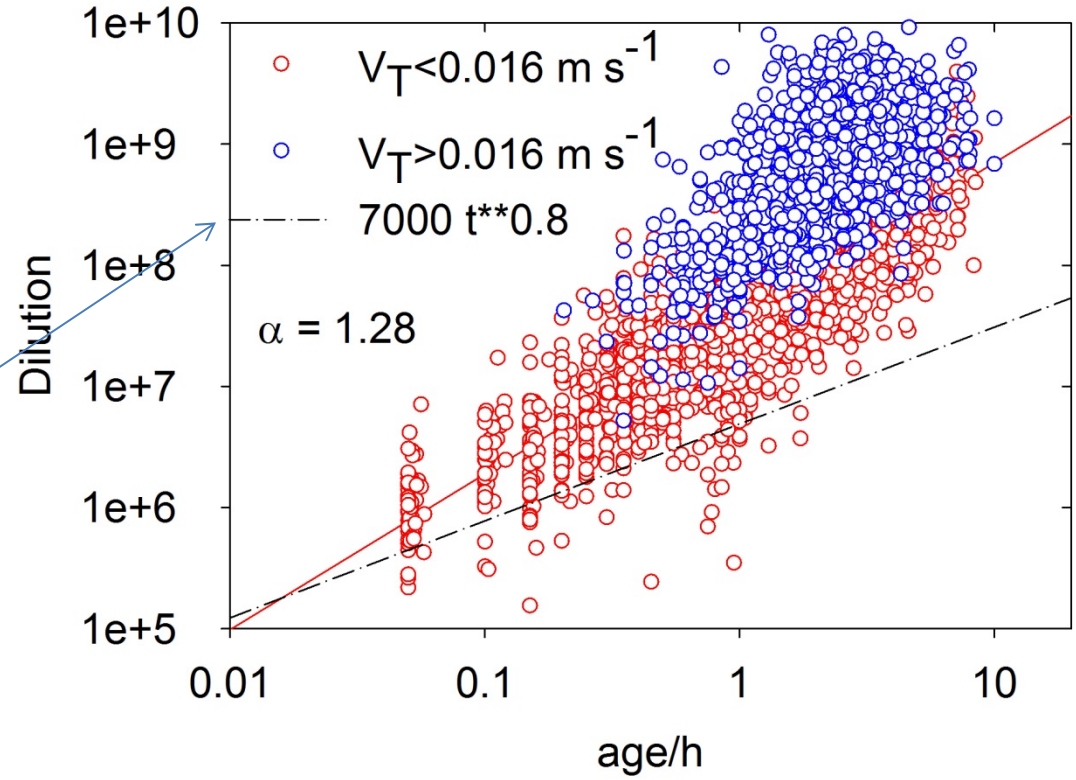
Dilution in contrails, stronger than for passive tracers and strongly enhanced by sedimentation (V_T = terminal fall velocity)

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

in contrails: $\alpha \approx 1.28$

passive tracers:

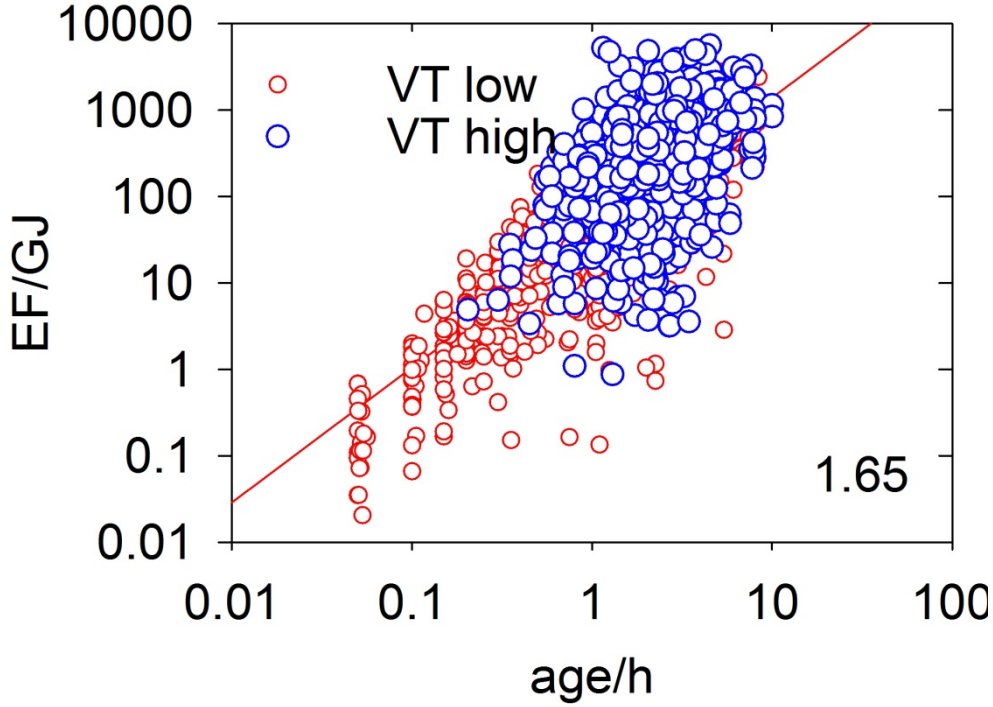
$$N_{dil} = 7000\,(t/t_0)^{0.8}$$



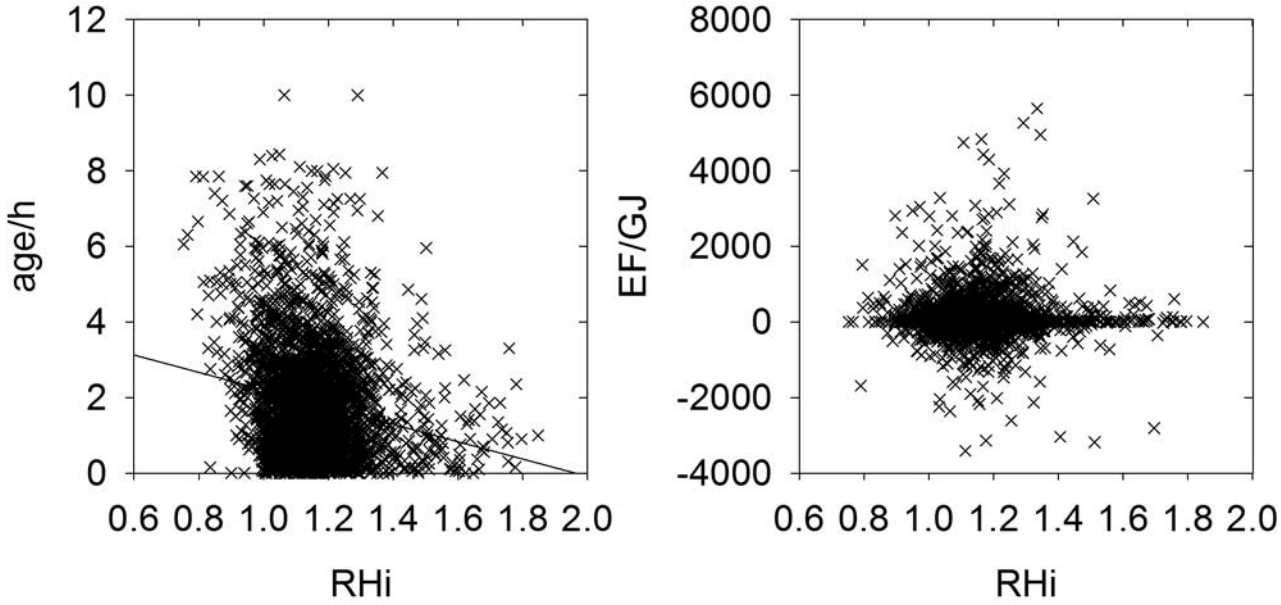
Energy Forcing: time integral of Wτ

$$EF = \frac{dRF'}{d\tau}\left[\frac{9\pi}{16\rho_{ice}^2}\right]^{1/3} C Q_{ext} m_F \left[f_s f_c PEI_{soot}\right]^{1/3} \left[\frac{(RHi-1) M_{H2O}\, p_{ice}(T)}{M_{air}\, p}\right]^{2/3} \frac{a}{1+2\alpha/3}(lifetime)^{1+2\alpha/3}$$

increase with age **(1.65±0.2)



Which contrails cause largest age and climate impact (EF)

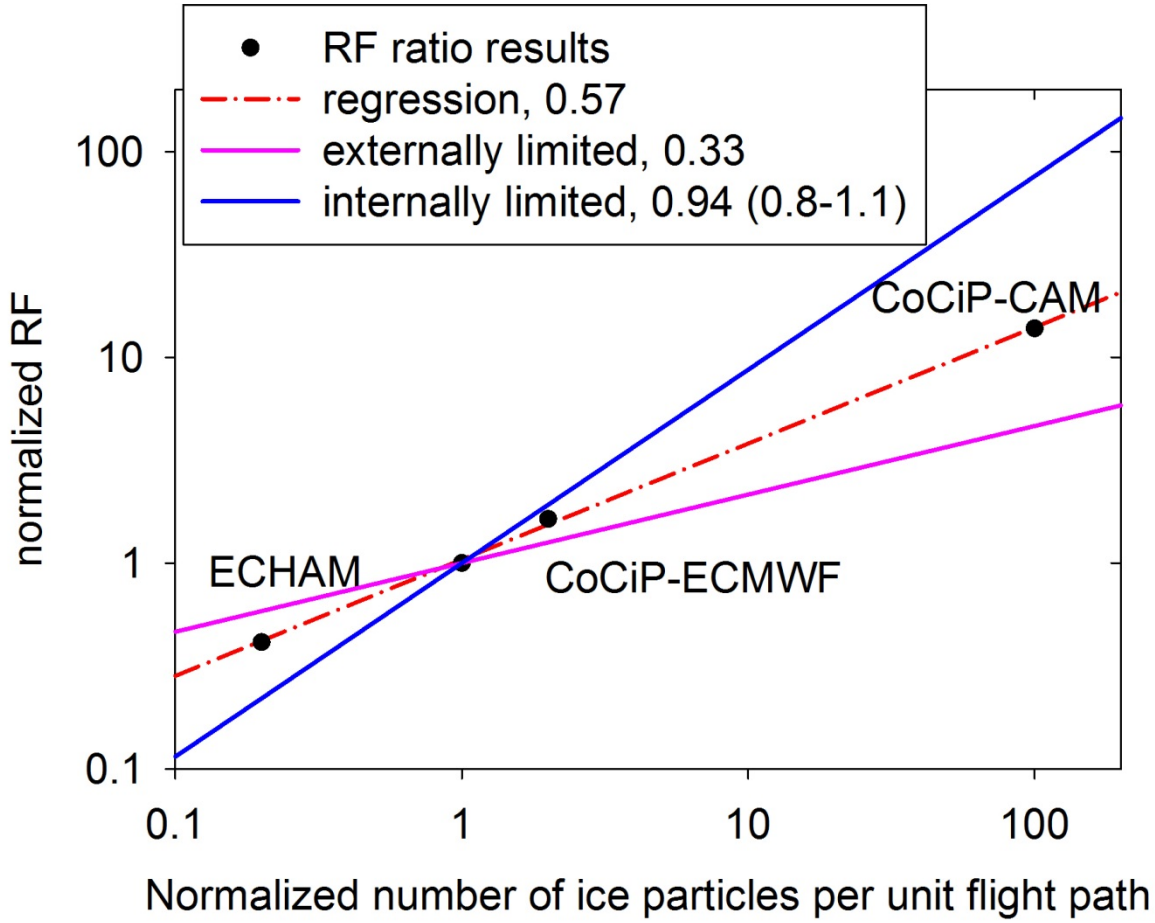


- weakly supersatured air

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±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