



Radiative heating in contrail cirrus

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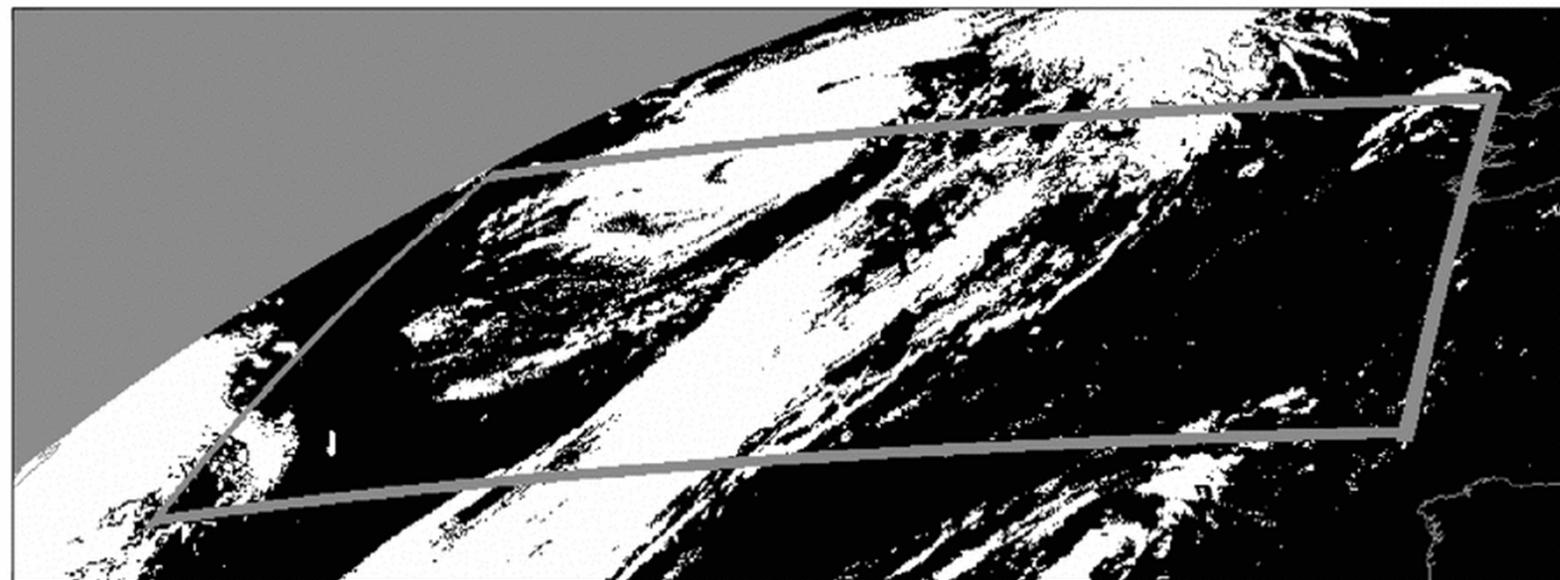
Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Institut für Physik der Atmosphäre - in Kooperation mit MIM/LMU München

Air traffic density in km / (km² h), 25.04.2004, 00:00 UTC



MeCiDA cirrus classification, 25.04.2004, 00:00 UTC



from
Meteosat
IR data,
MeCiDa

Graf et
al. (2009)

A new model

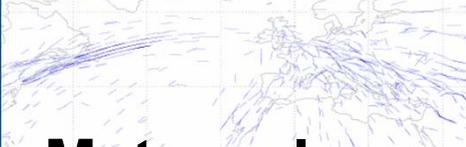
Contrail Cirrus Simulation and Prediction (CoCiP)

Input:
Aircraft
(BADA)



Movements
(Eurocontrol,
OAD, DFS)

00:00
00208

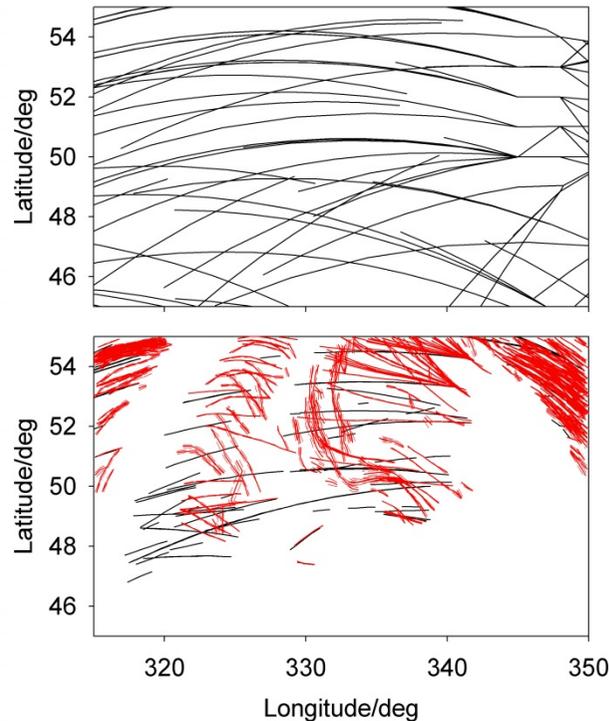


Meteorology
(NWP results,
ECMWF, DWD)



Contrail Cirrus
Prediction Tool

NAR, 12. Aug 2005, 3-6 UTC



- From regional to global
- Comparable to observations

Output:
Contrail,
life cycle,
cover, radiation

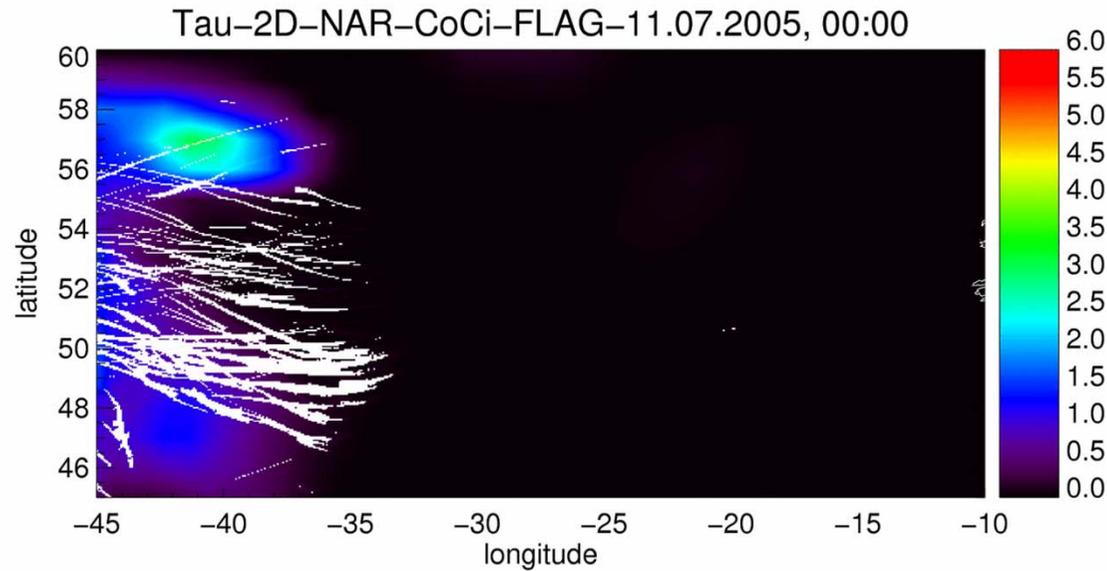
Cirrus

Simulation
insitu, Lidar,
Satellite

Sensitivity
studies

Prediction
Climate impact





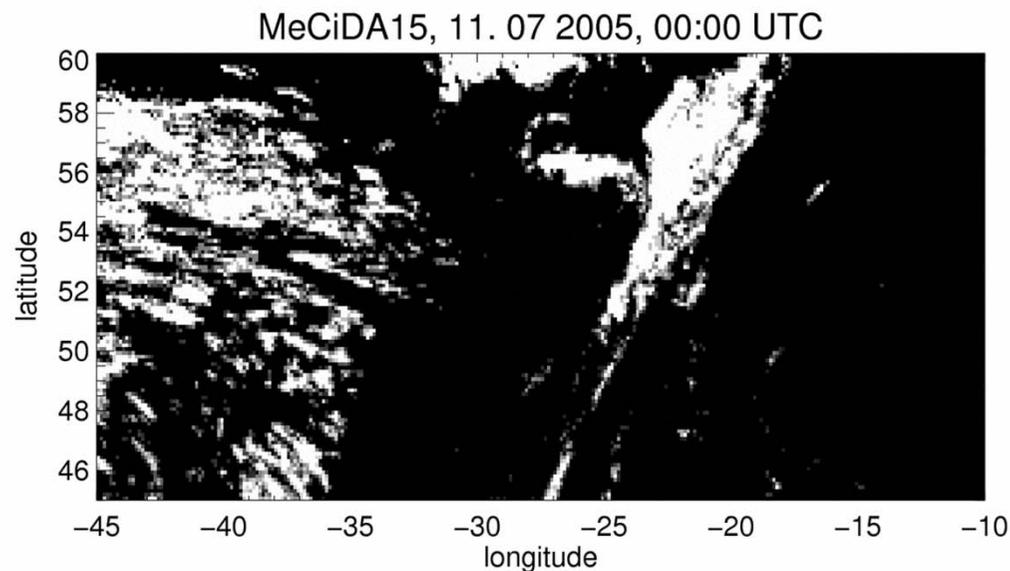
North Atlantic Region (NAR)

Top:

Color scale: cirrus cloud optical thickness

τ

white: $\tau_{\text{Contrail}} > 0.1$

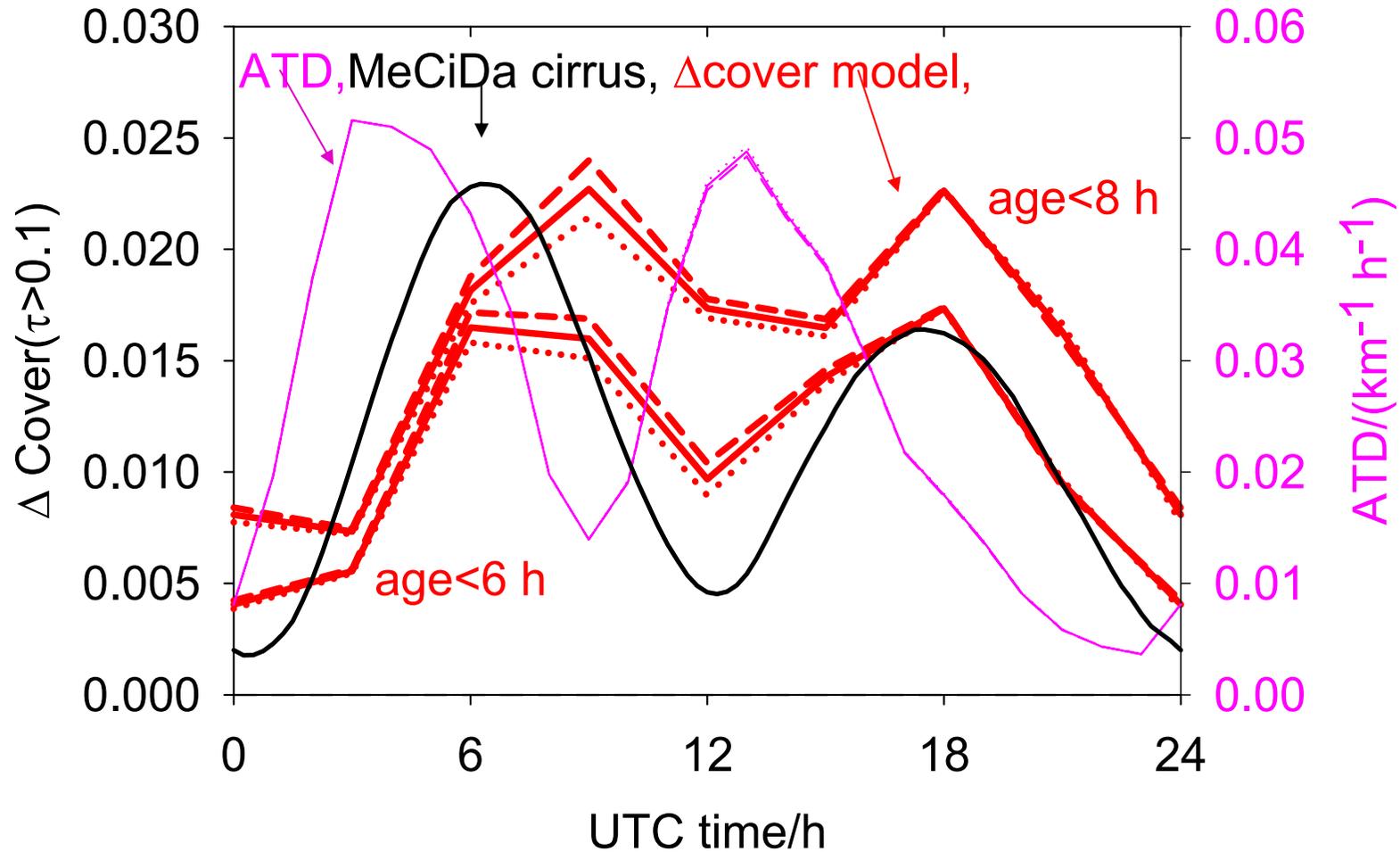


Bottom:

Meteosat (MSG)-MeCiDa observation derived cirrus cover (white)

Cover in North Atlantic Region, compared to MeCiDa cirrus cover (derived from Meteosat IR channels)

Question: does solar heating contribute to limiting cirrus cloud life time?



Effects of Heating in Cirrus

e.g.: Ackerman et al. (1988)

SW: warming

LW: heating/cooling

Causes:

lofting

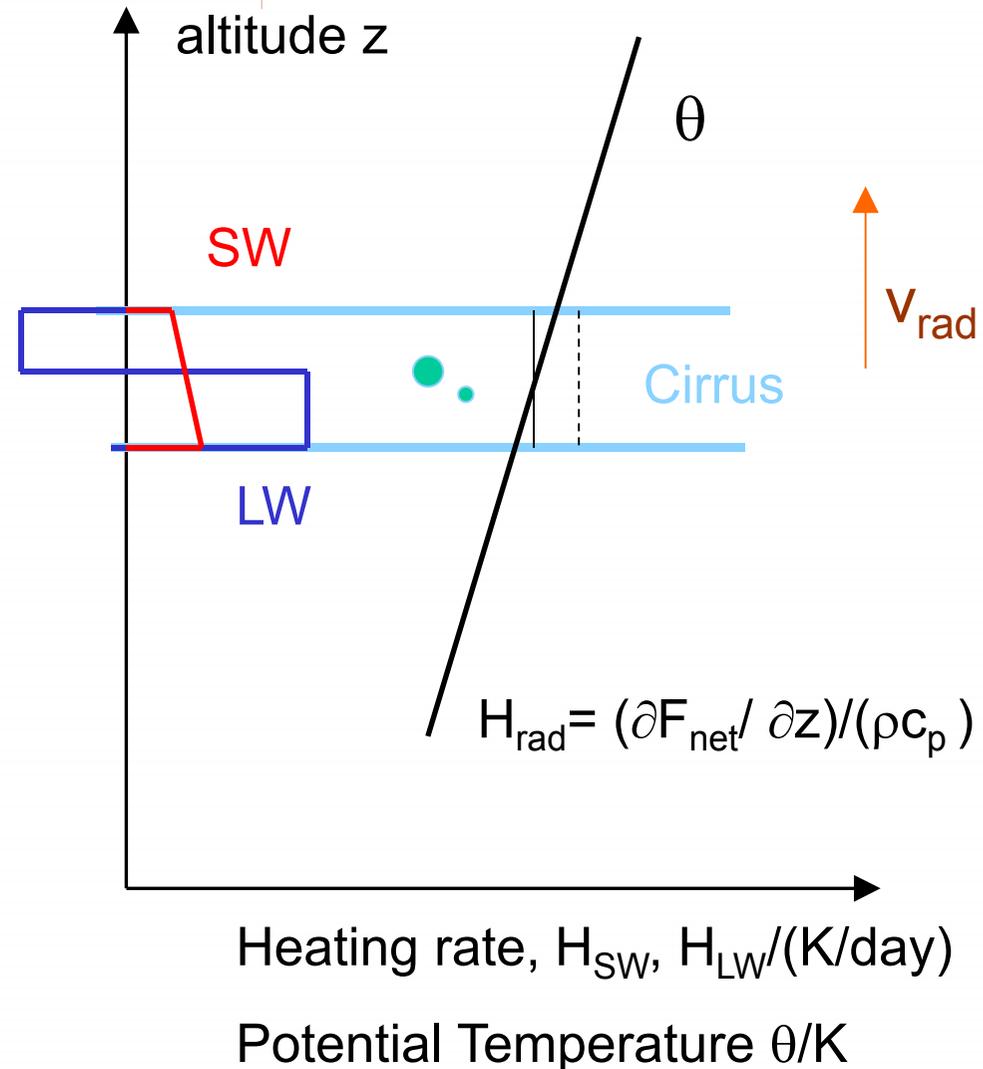
convective turbulence

Drying of cloud layer

Sublimation of **ice particles**

(e.g. Gierens 1996)

$$V_r = H_{rad}(d\Theta/dz)$$



Enhanced vertical diffusivity

radiation induced buoyancy = dissipation of kinetic energy

$$B = g H Q/T \quad \epsilon_{kin} = w_*^3/H$$

$$w_* = (g H^2 Q/T)^{1/3}$$

$$D_{zz} = \frac{0.4}{N_{BV}} \max(w_N^2, w_*^2)$$

enhanced vertical mixing (diffusivity D_{zz}),

also causing enhanced lateral shear driven mixing



Radiative forcing (RF) analysis: Model Setup

Input from CoCiP:

θ : solar zenith angle (SZA)

r : effective ice particle radius (μm)

T_C : contrail temperature (K)

τ : contrail optical depth

θ : solar zenith angle (SZA) ,

$$RF_{LW} = (OLR - \sigma_T T_C^{k_T}) [1 - \exp(-\delta_\tau \tau)] \times F_{LW}(r) \geq 0$$

$$RF_{SW} = -\mu S_0 (t_A - A_{\text{eff}})^2 C_{SW}(\mu, \tau) \times F_{SW}(r) \leq 0,$$

Input from NWP (ECMWF) data:

OLR : outgoing longwave radiation at TOA (W/m^2)

RSR : reflected solar radiation at TOA (W/m^2)

SDR : solar direct radiation (W/m^2)

S_0 : solar constant

effective albedo $A_{\text{eff}} = RSR/SDR$

$\mu = \cos \theta = SDR/S_0$

Fit parameters (6 for LW and 11 for SW) for the 6 habit classes from least squares fit,
 $S = \min:$

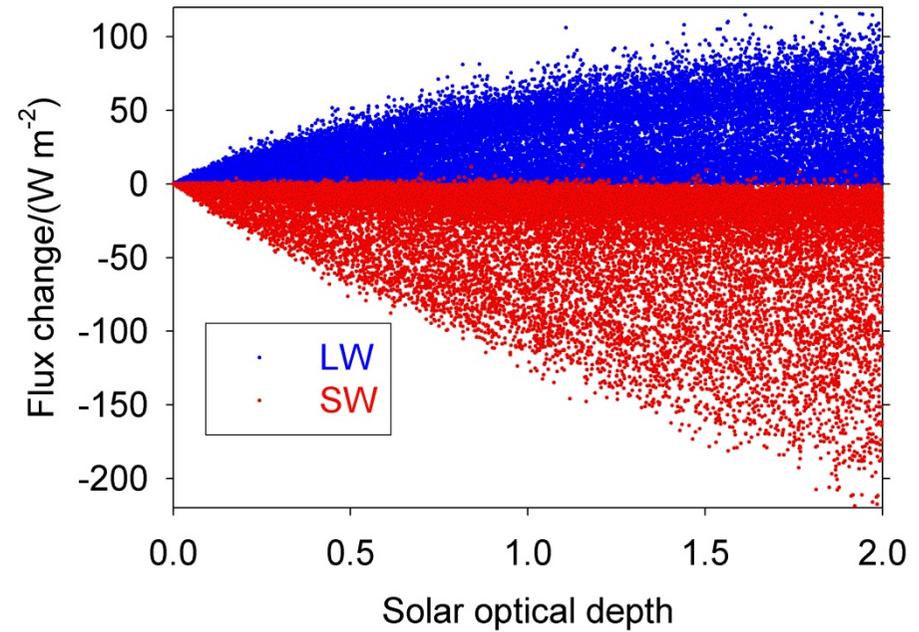
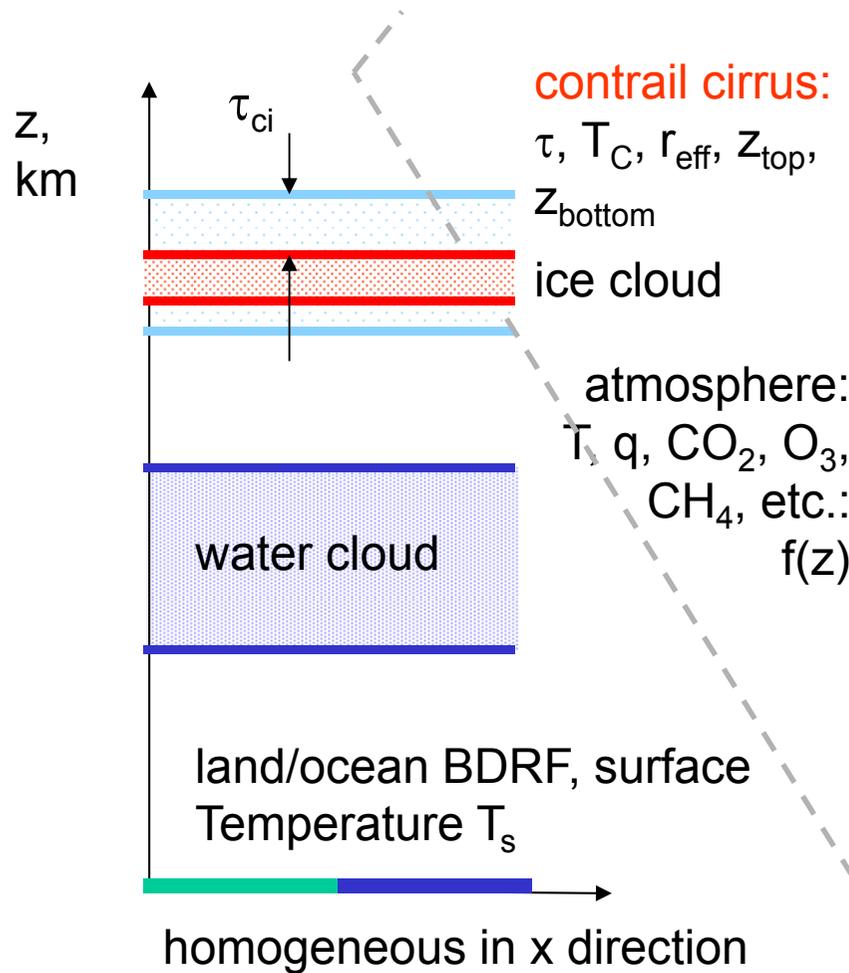
$$S = \sum_{all\ data} (data - fit)^2$$

further factors account for optical depth τ_{ci} of cirrus above contrail:
 less important for RF but important for internal heating rates

(Schumann et al., 2009)

Forward calculations with libRadtran

Forward simulations for 31928 cases
libRadtran (Mayer and Kylling, 2005).



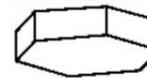
for 7 ice
particle
habits:



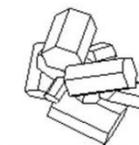
sphere



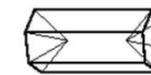
droxtal



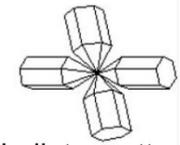
plate



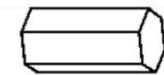
aggregate



hollow column



bullet rosette



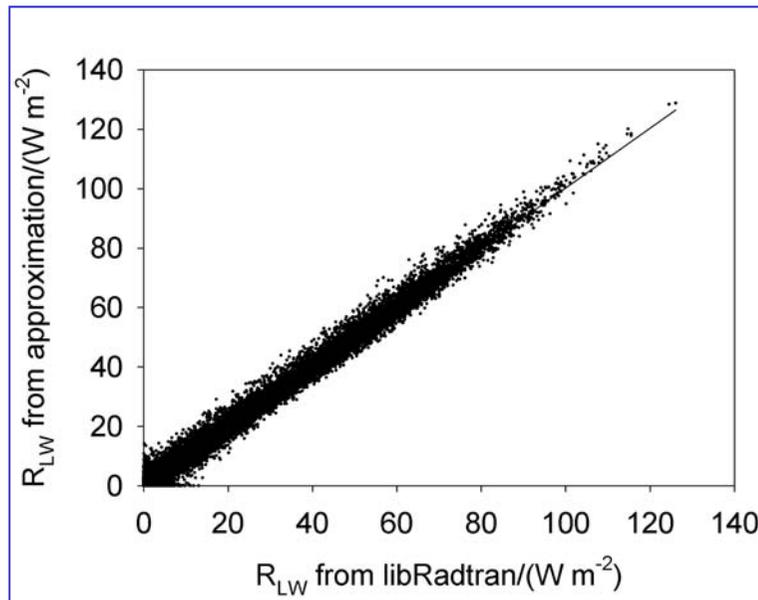
solid column



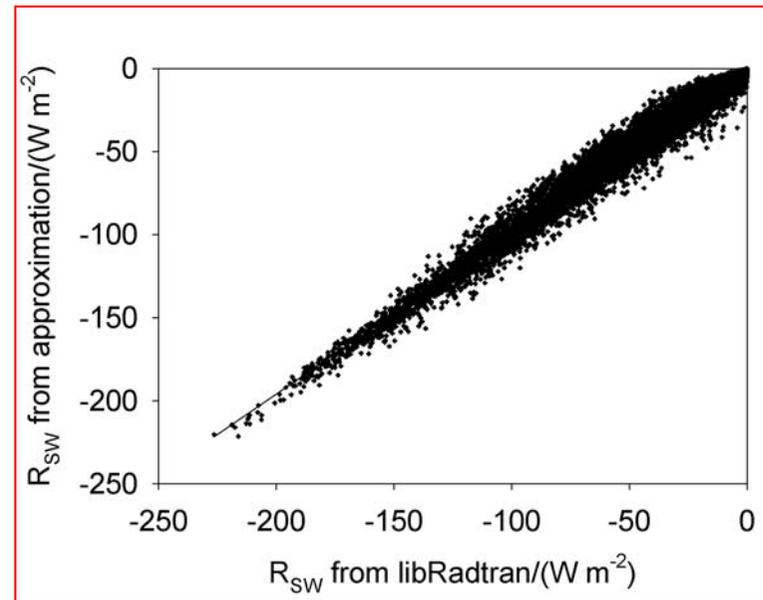
Fit results

$$RF_{LW} = (OLR - \sigma_T T_C^{kT}) [1 - \exp(-\delta_\tau \tau)] \\ \times F_{LW}(r) \geq 0$$

$$RF_{SW} = -\mu S_0 (t_A - A_{\text{eff}})^2 C_{SW}(\mu, \tau) \\ \times F_{SW}(r) \leq 0,$$

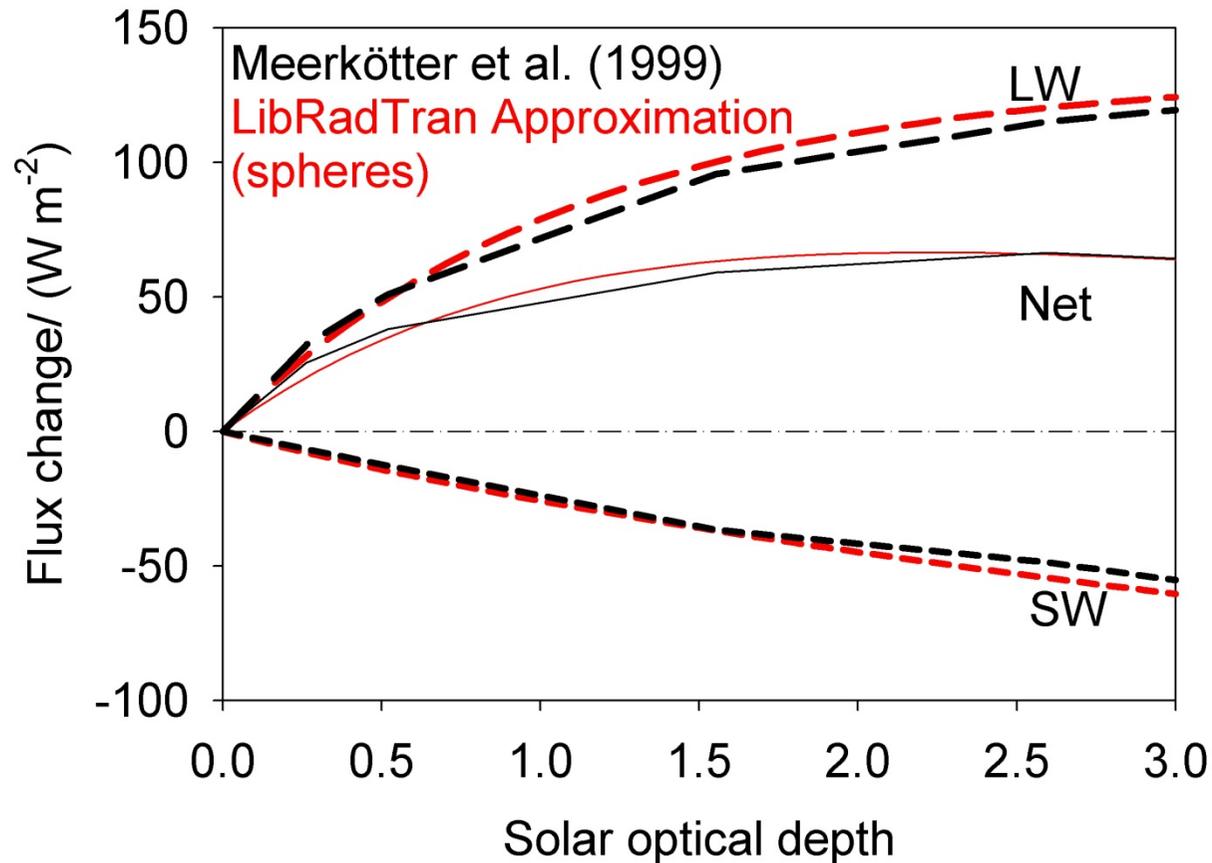


LW, $r = 0.99$



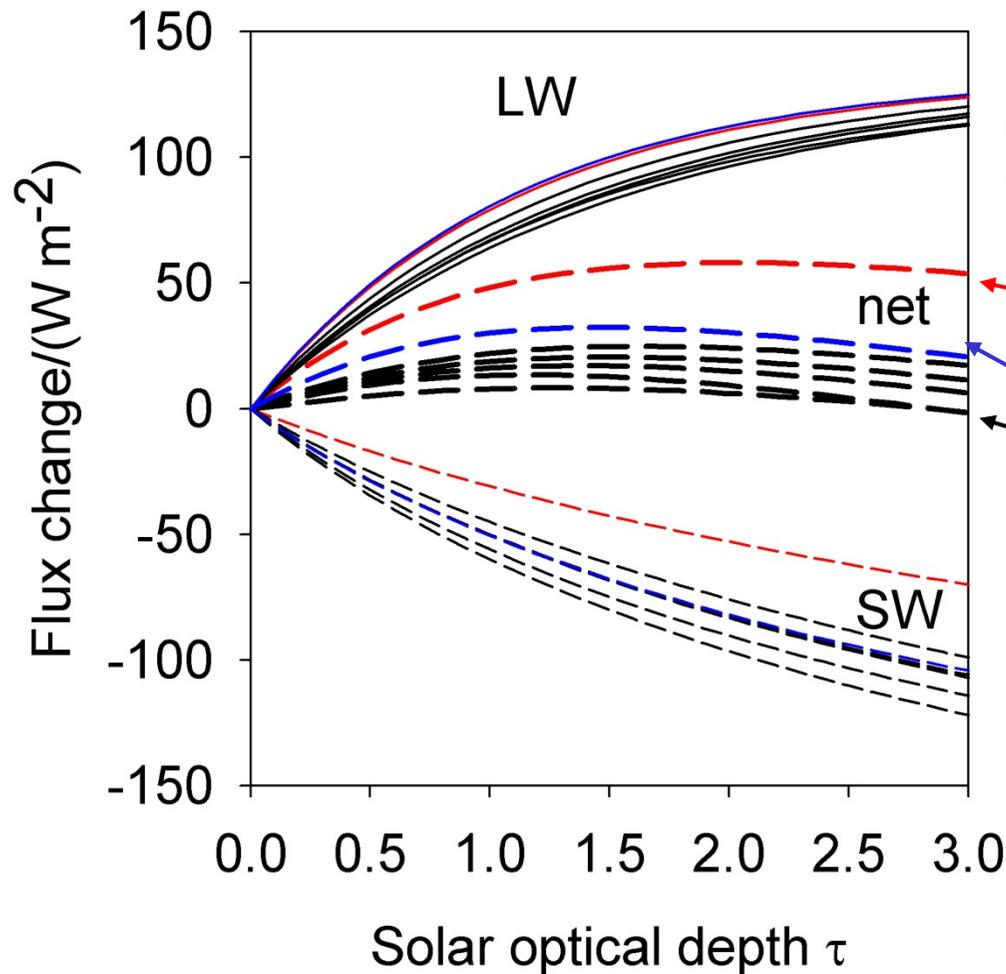
SW, $r = 0.98$

Approximation versus previous benchmark: Daily mean RF versus τ

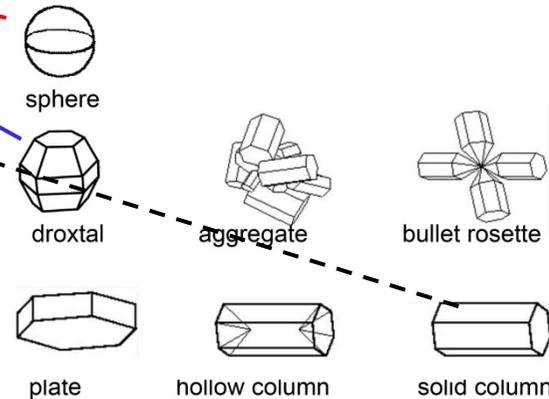


Daily mean
100 % cover
cirrus layer
 $z=10.8-11$ km
summer standard
atmosphere
 $A_{\text{surf}}=0.2$
 45° latitude
 $T_{\text{surf}} = 20.8^\circ\text{C}$
 $r_{\text{eff}} = 16 \mu\text{m}$
spheres

RF may change sign depending on cirrus particle habits



$R=16 \mu\text{m}$, 45°N , summer
day-mean, $A_g=0.2$,
 $T_C = -44.6^\circ\text{C}$, $T_B = -8.2^\circ\text{C}$



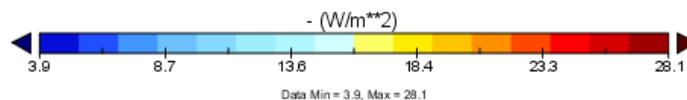
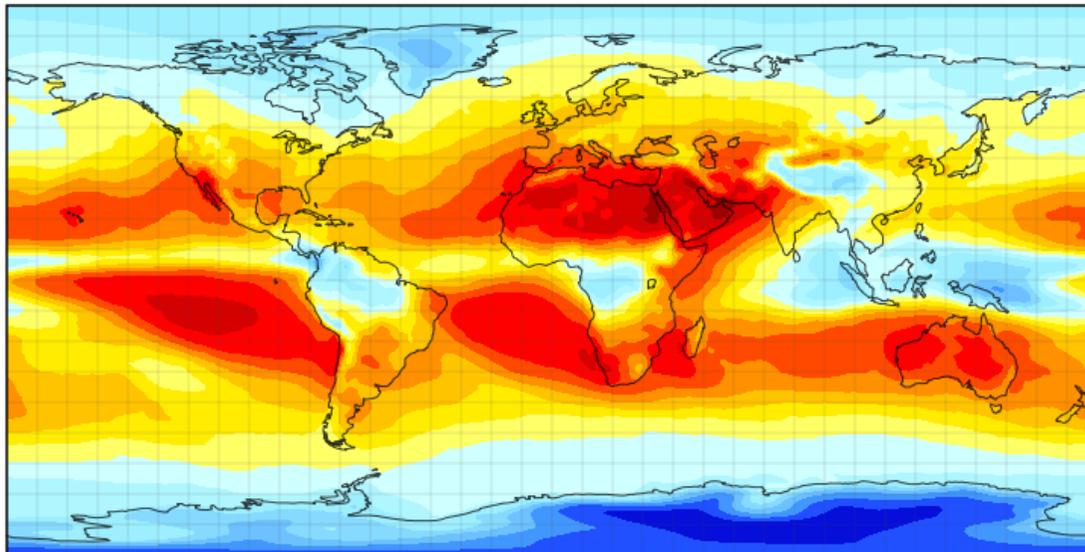
CoCiP assumes size-dependent contrail cirrus habit mix:

100 % droxtals for volume mean radius 0 – 5 μm ,
70 % droxtals + 30 % solid columns for 5 – 10 μm ,
40 % droxtals + 30 % solid columns + 30 % 3D bullet rosettes for 10 – 30 μm .
Larger contrail particles: same as natural cirrus (Baum et al., 2005)

Comparing with Myhre et al. (2009):

1% homogeneous cover of
cirrus with $\tau=0.3$,
annual mean

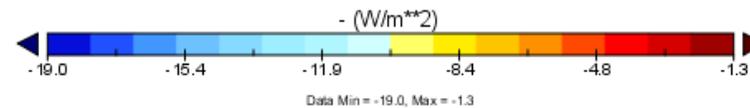
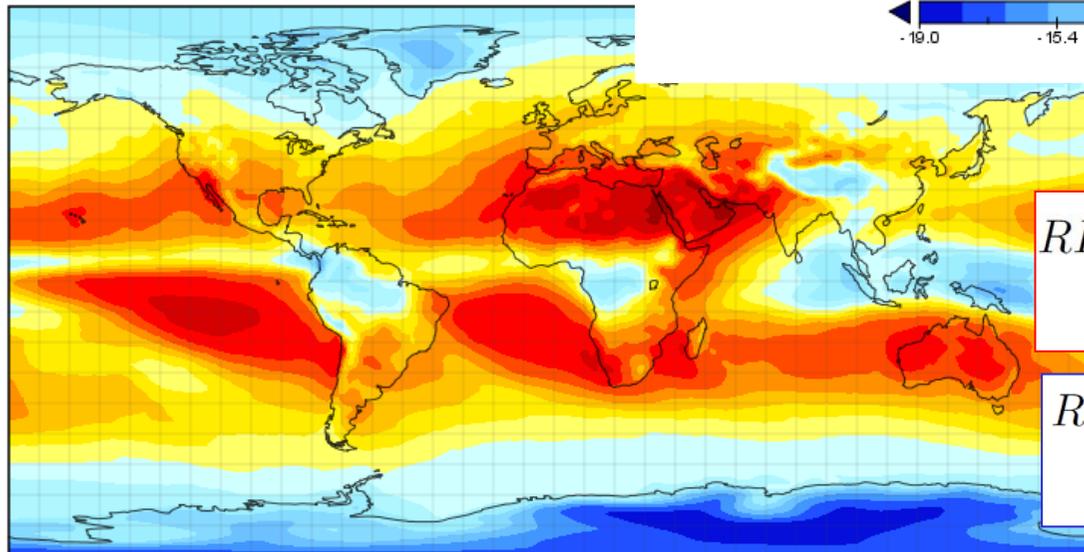
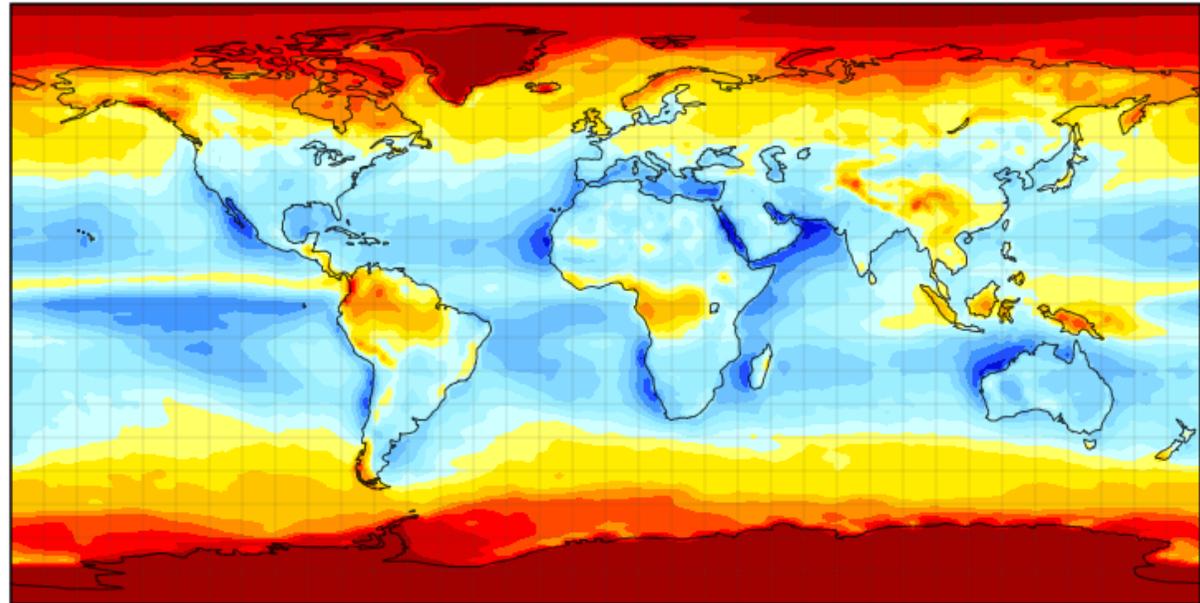
$$RF_{LW} = (OLR - \sigma_T T_C^{kT}) [1 - \exp(-\delta_\tau \tau)] \\ \times F_{LW}(r) \geq 0$$



LW: 4 to 28 W/m²

Comparing with
Myhre et al. (2009):

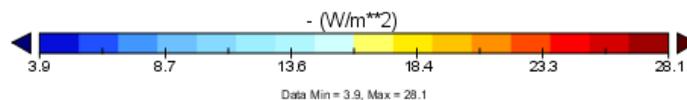
1% homogeneous cover of
cirrus with $\tau=0.3$,
annual mean



SW: -19 to -1 W/m²

$$RF_{SW} = -\mu S_0 (t_A - A_{\text{eff}})^2 C_{SW}(\mu, \tau) \times F_{SW}(r) \leq 0,$$

$$RF_{LW} = (OLR - \sigma_T T_C^{k_T}) [1 - \exp(-\delta_\tau \tau)] \times F_{LW}(r) \geq 0$$

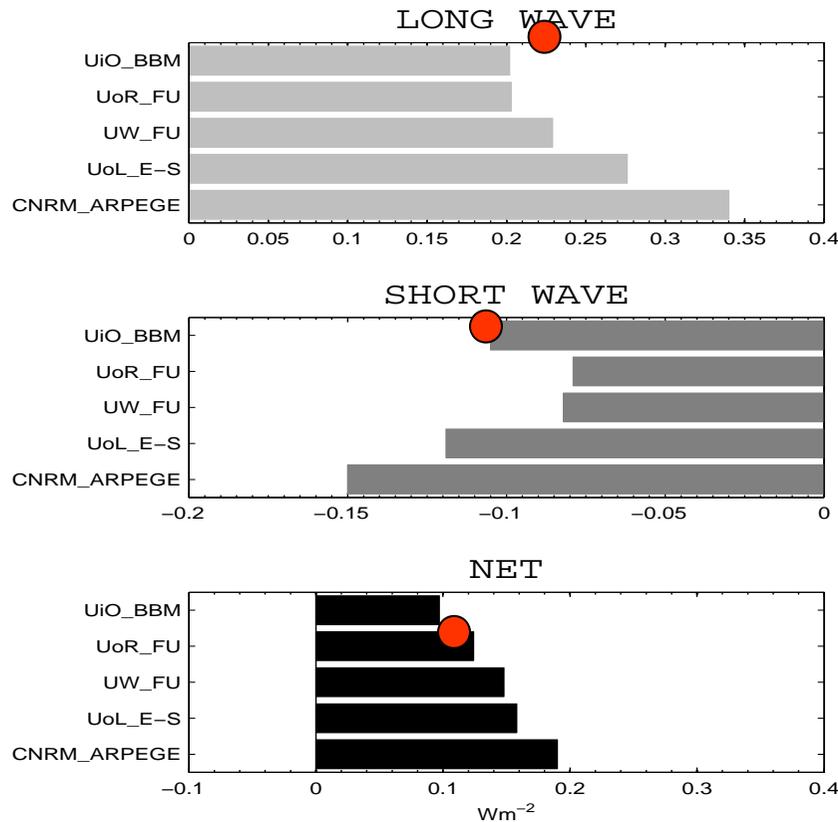


LW: 4 to 28 W/m²

Comparison with mean RF values (Myhre et al., 2009)

(Myhre et al., 2009): bars

CoCiP 2005: colored dots



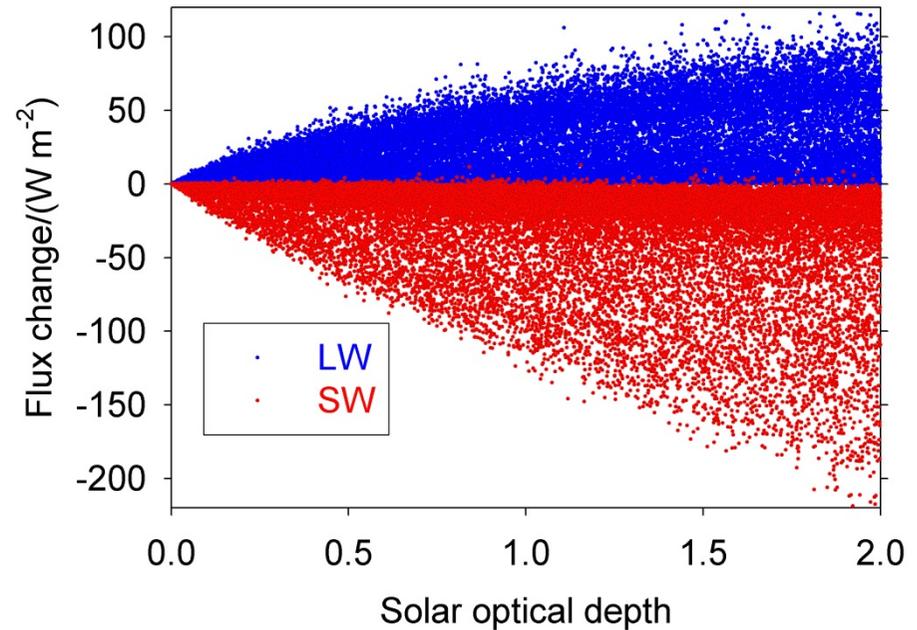
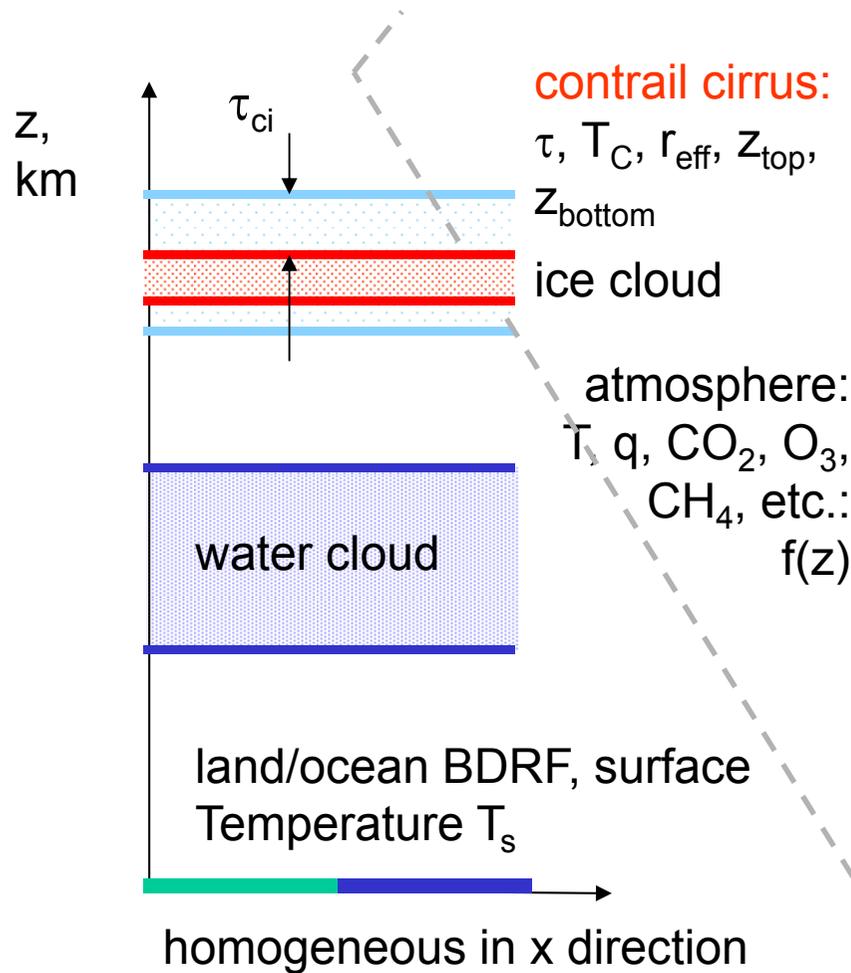
LW: 0.213 W/m^2

SW: -0.118 W/m^2

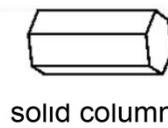
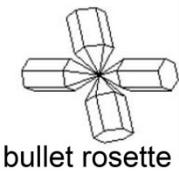
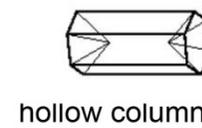
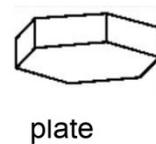
Net, SW+LW: 0.095 W/m^2

Forward calculations with libRadtran

Forward simulations for 31928 cases
libRadtran (Mayer and Kylling, 2005).



for 7 ice
particle
habits:



Modeling as a function of TOA radiances and mean cirrus properties

Top of Atmosphere radiances

(ECMWF):

S_0 : solar constant

SDR: solar direct radiation

RSR: reflected solar radiation

OLR: outgoing longwave radiation

τ : solar optical depth contrail cirrus

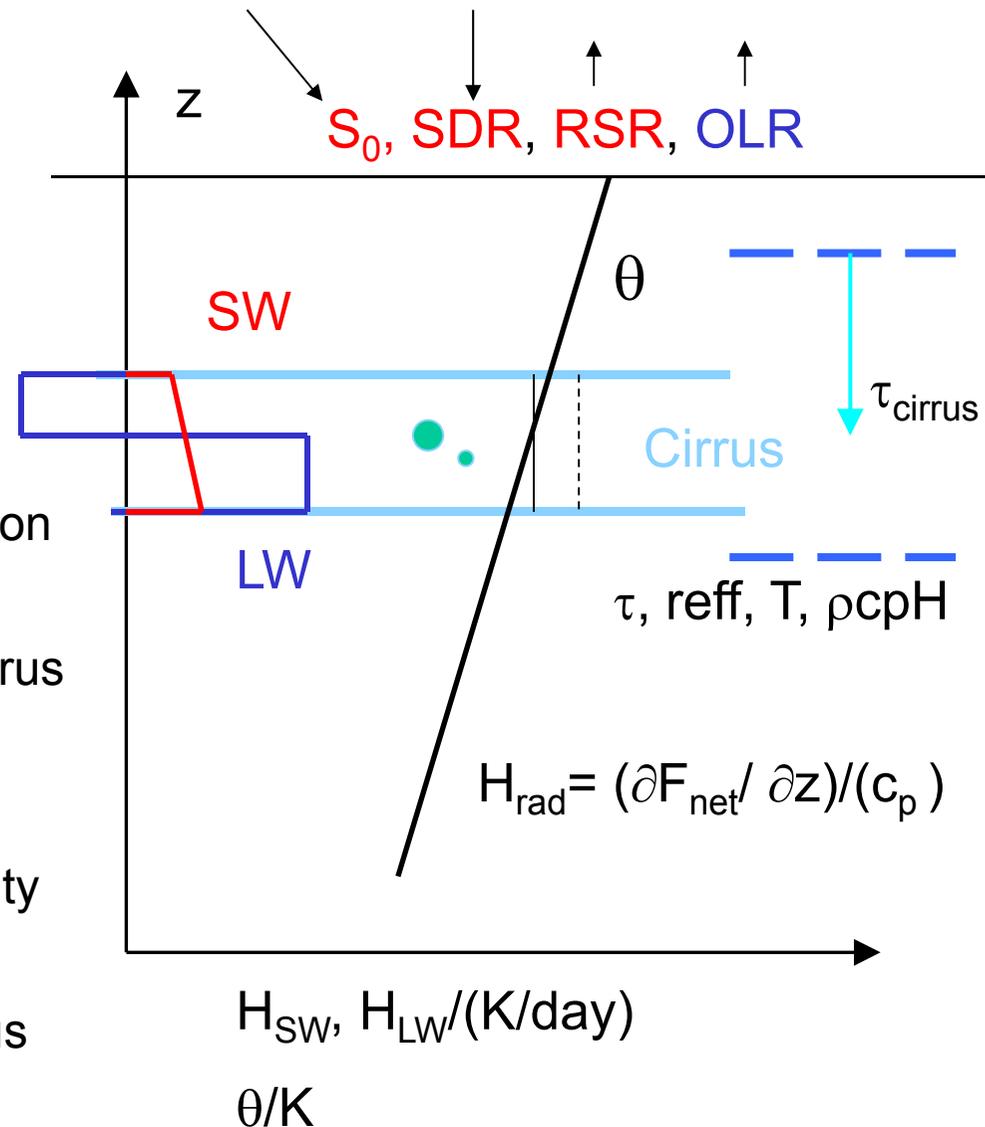
r_{eff} : effective radius ($= C \cdot r_{\text{vol}}$)

T : mid cirrus temperature

$\rho c_p H$: contrail cirrus heat capacity

habit mix

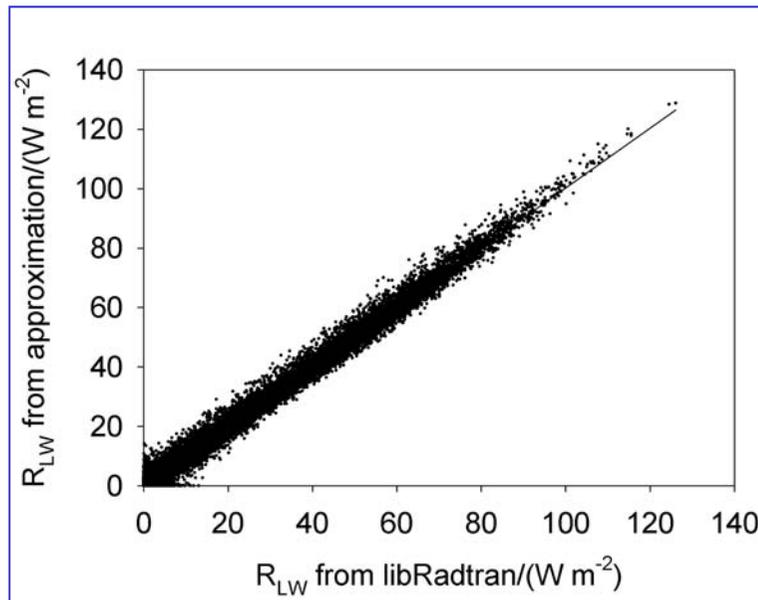
τ_{cirrus} : solar optical depth of cirrus above contrail cirrus



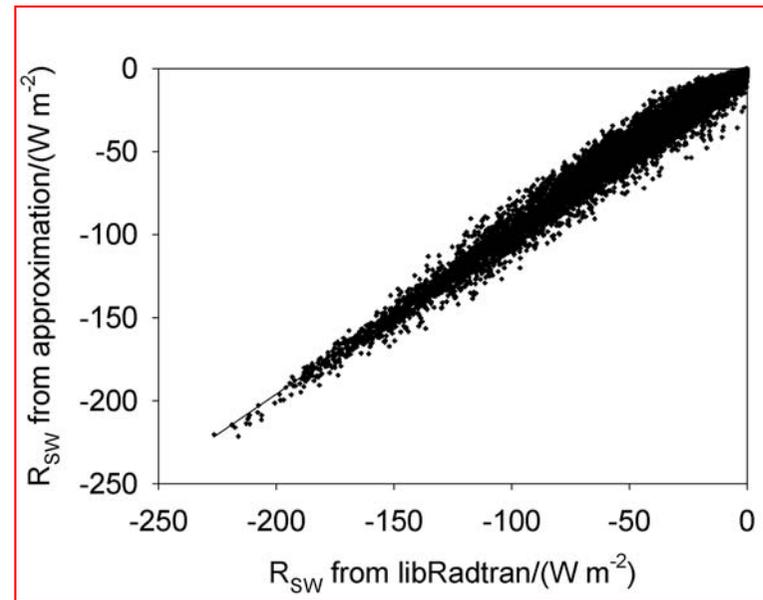
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LW, $r = 0.99$



SW, $r = 0.98$

Fit parameters (6 for LW and 11 for SW) for the 6 habit classes from least squares fit of model to libRadtran results

(Schumann et al., 2009)

Radiative forcing (RF) analysis: Model Setup

Input from CoCiP:

θ : solar zenith angle (SZA)

r : effective ice particle radius (μm)

T_C : contrail temperature (K)

τ : contrail optical depth

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SDR : solar direct radiation (W/m^2)

S_0 : solar constant

effective albedo $A_{\text{eff}} = RSR/SDR$

$\mu = \cos \theta = SDR/S_0$

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$$S = \sum_{all\ data} (data - fit)^2$$

further factors account for optical depth τ_{ci} of cirrus above contrail:
less important for RF but important for internal heating rates

(Schumann et al., 2009)

Radiative heating rates

H. average over the cirrus layer

DH: difference between upper and lower half of the cirrus layer

Results of libRadtran (disort) versus solar optical depth τ based on 27279 forward calculations for different atmospheres and contrail cirrus

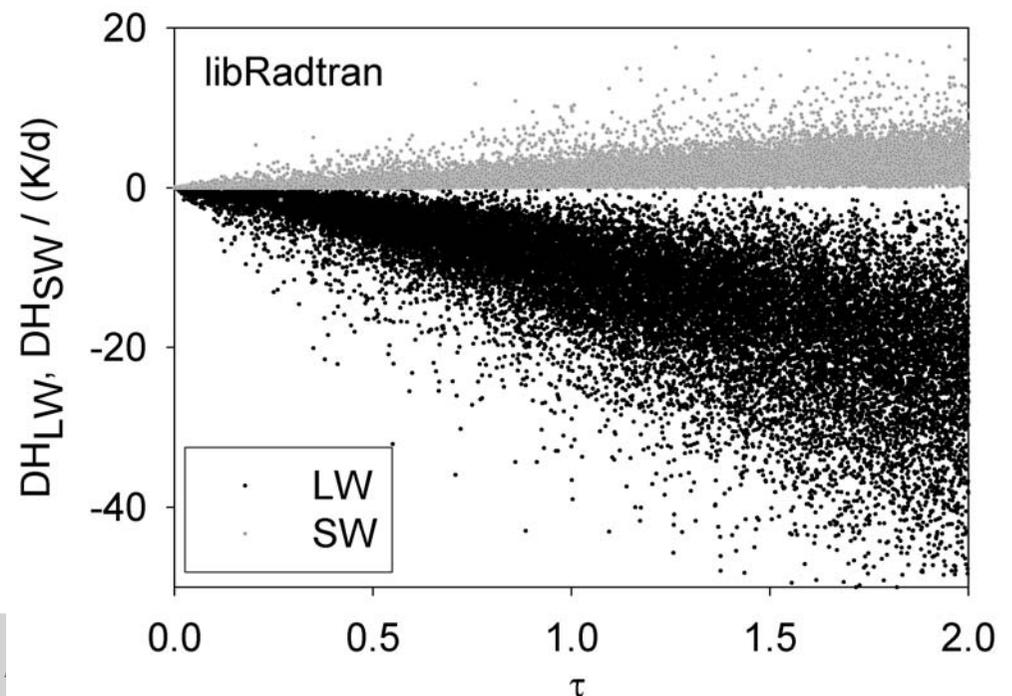
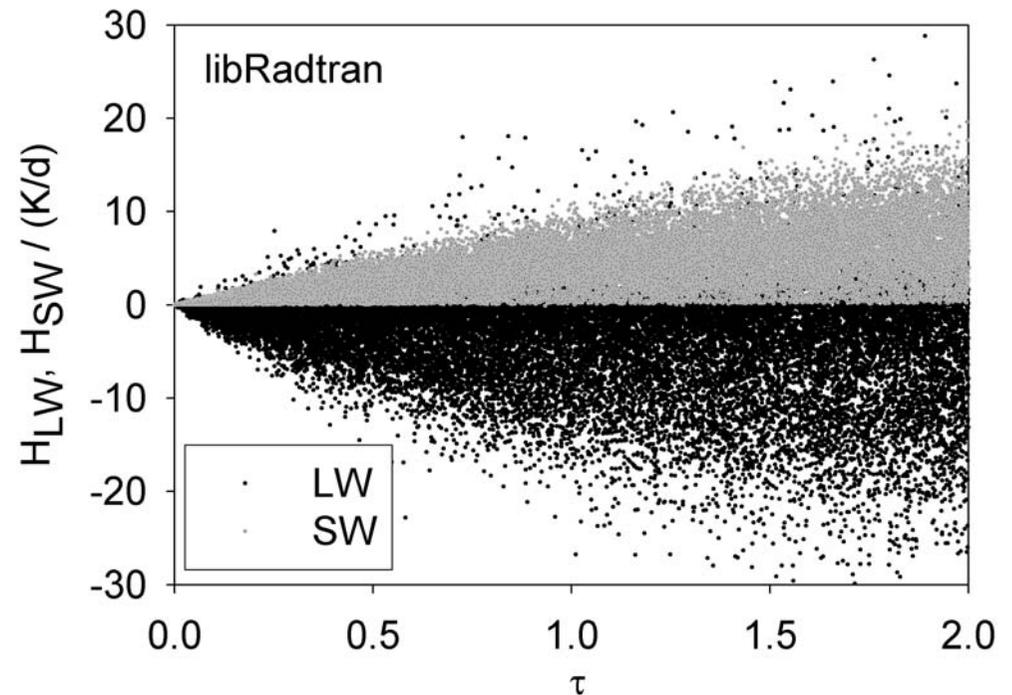
H_{LW} is positive or negative

H_{SW} is positive

DH_{LW} is negative

DH_{SW} is positive

Both are zero for $\tau=0$, and increase or decrease monotonically with τ .



Model Setup

Heating rate (H) and differential heating rate (DH), SW and LW:

$$H_{SW}, DH_{SW} = \tau (a' SDR \pm b' RSR) f(RSR, SDR, S_0, \tau, \tau_{cirrus}, r_{eff}, habit) / (\rho c_p)$$

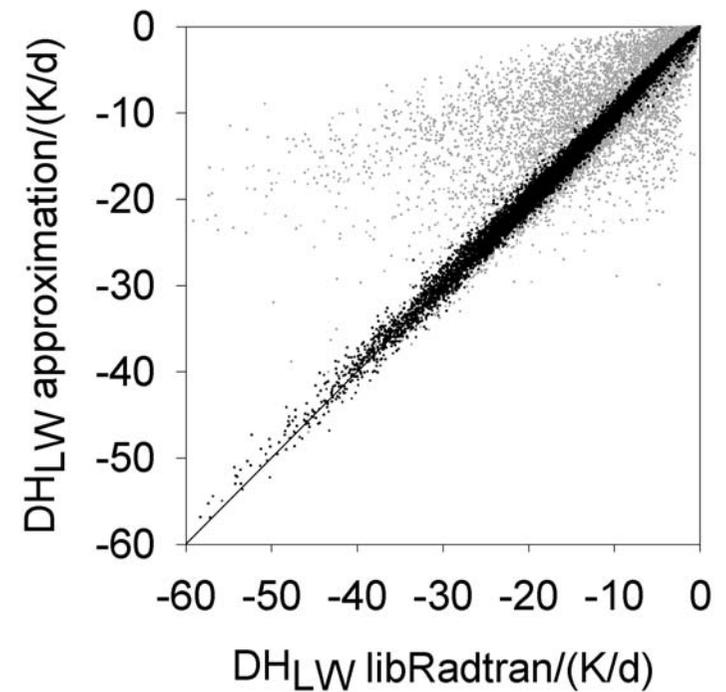
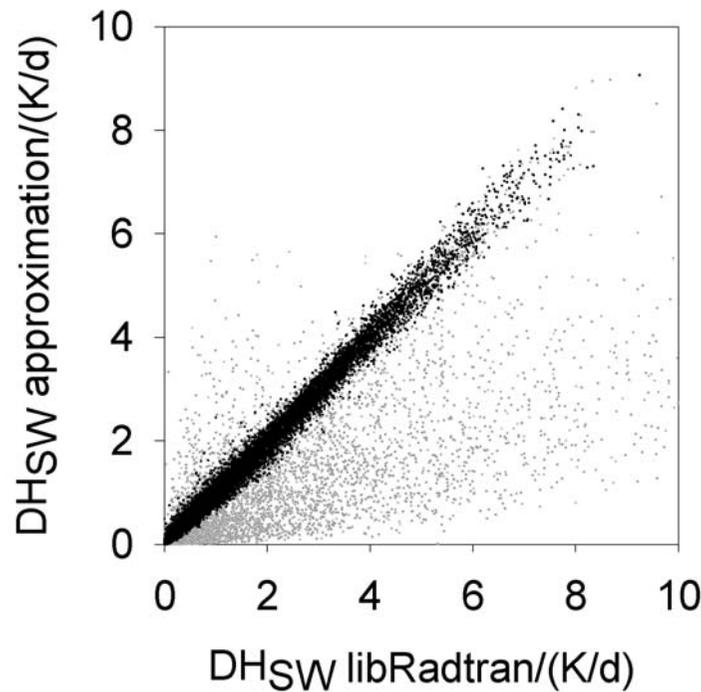
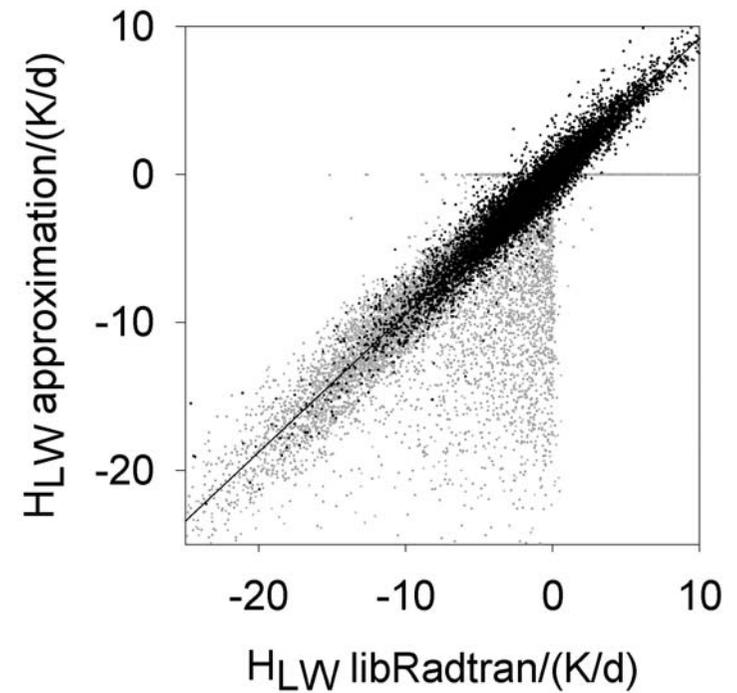
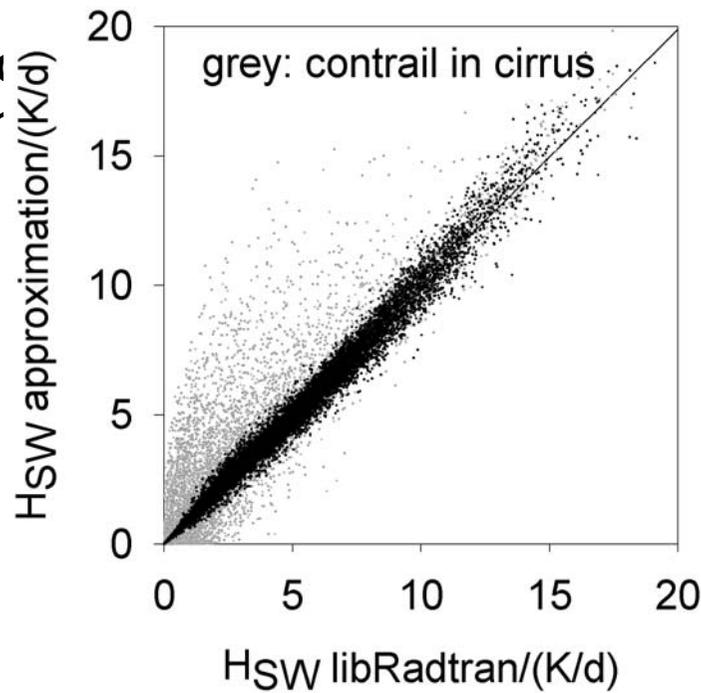
$$H_{LW}, DH_{LW} = (1 - \exp(-\delta \tau)) (a'' OLR \pm b'' \sigma T^4) f(RSR, SDR, S_0, \tau, \tau_{cirrus}, r_{eff}, habit) / (\rho c_p)$$

each containing **10 free coefficients** per habit, fitted to libRadtran results

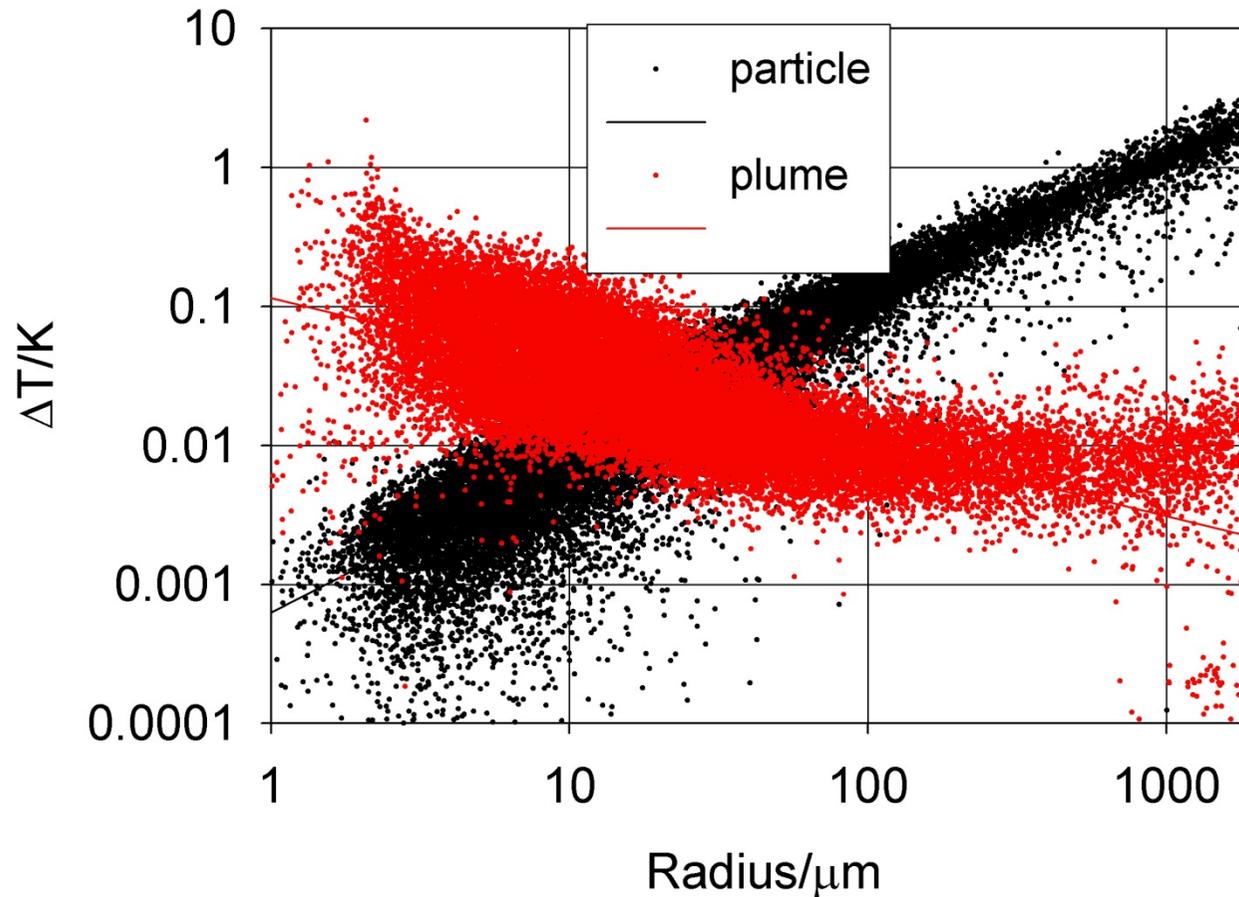
libRadtran and approximator for H and DH, SW and LW.

Black: contrail cirrus outside other cirrus.

Gray: contrail cirrus inside other cirrus.



Temperature changes due to ice particle and plume heating



Both effects are important, but for particles of different sizes

Conclusions

Heating in contrail cirrus (thin cirrus) in the upper troposphere important:

Lofting (weak compared to sedimentation)

Convective turbulence inducing strong impact on vertical mixing and lateral widening of contrail plumes (strong compared to shear induces turbulence in stably stratified layers)

Warming of the bulk cirrus layer, and hence dry out at time scale of order 10 h

Dry-out of large ice particles (short time scales)

Other effect limiting life time: mesoscale vertical turbulent motions

Missing: quantitative measurements to verify approximate models