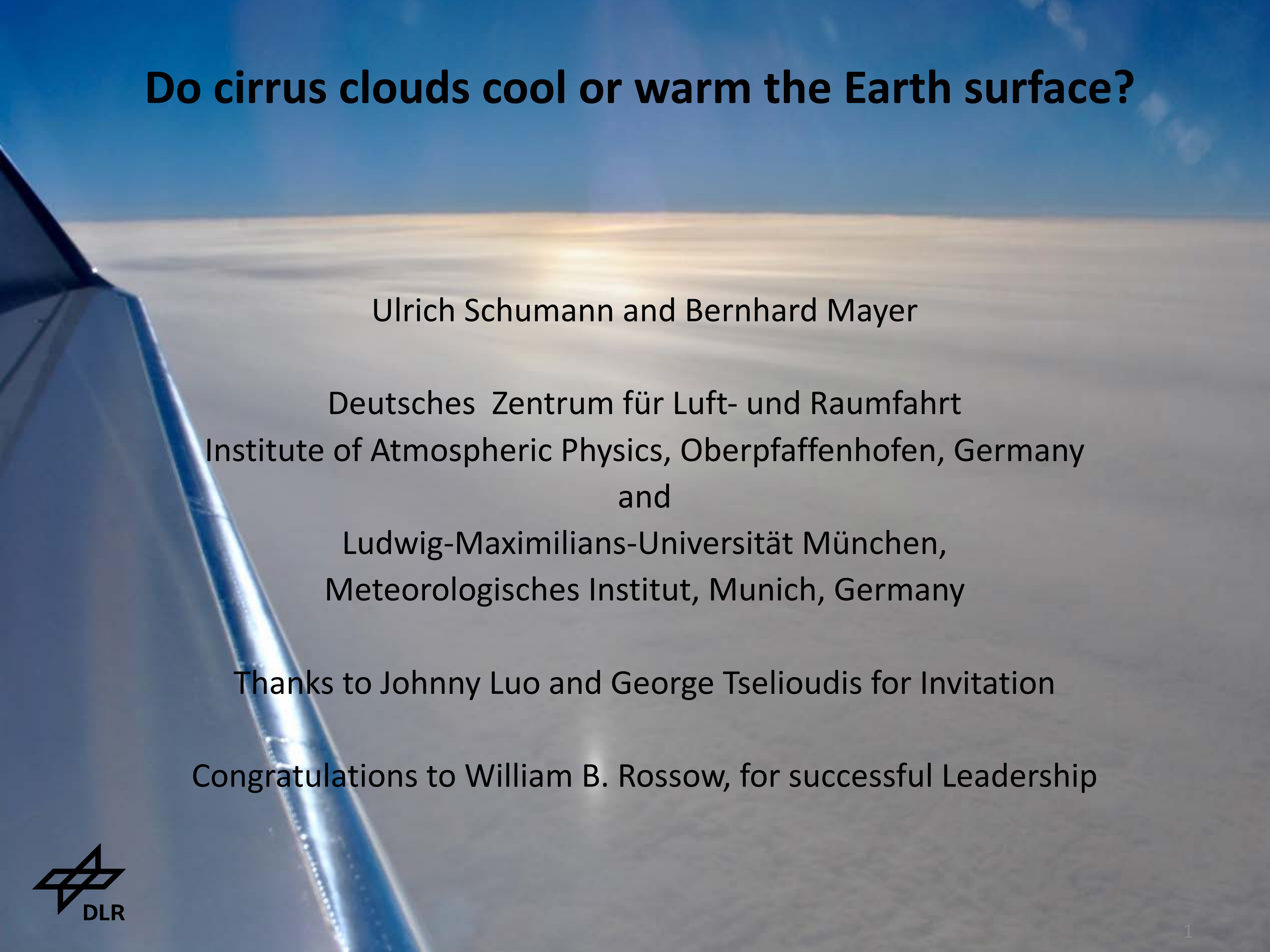
Do cirrus clouds cool or warm the Earth surface?



Ulrich Schumann and Bernhard Mayer

Deutsches Zentrum für Luft- und Raumfahrt
Institute of Atmospheric Physics, Oberpfaffenhofen, Germany
and
Ludwig-Maximilians-Universität München,
Meteorologisches Institut, Munich, Germany

Thanks to Johnny Luo and George Tselioudis for Invitation

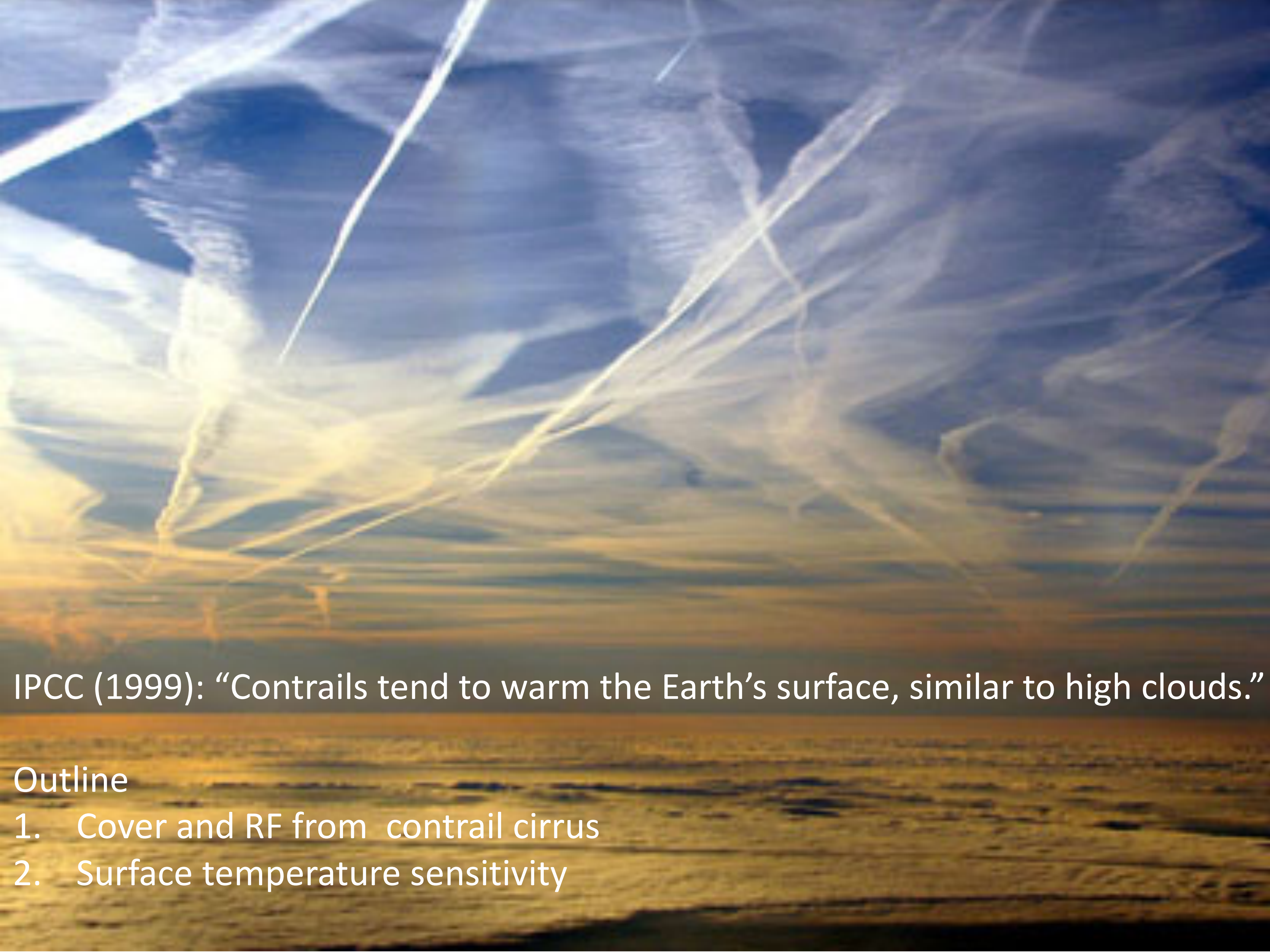
Congratulations to William B. Rossow, for successful Leadership

Do cirrus clouds cool or warm the Earth surface?

- heat the upper troposphere
- cool near the surface
- the net surface temperature effect depends on many complex feedbacks

- less coverage
- optically thinner
- sporadic
- short lived
- more over continents than over oceans
- smaller ice crystals
- more during daytime than during night
- -> stronger SW cooling
- localized at mid latitudes
- air traffic controlled -> less sensitive to feedbacks

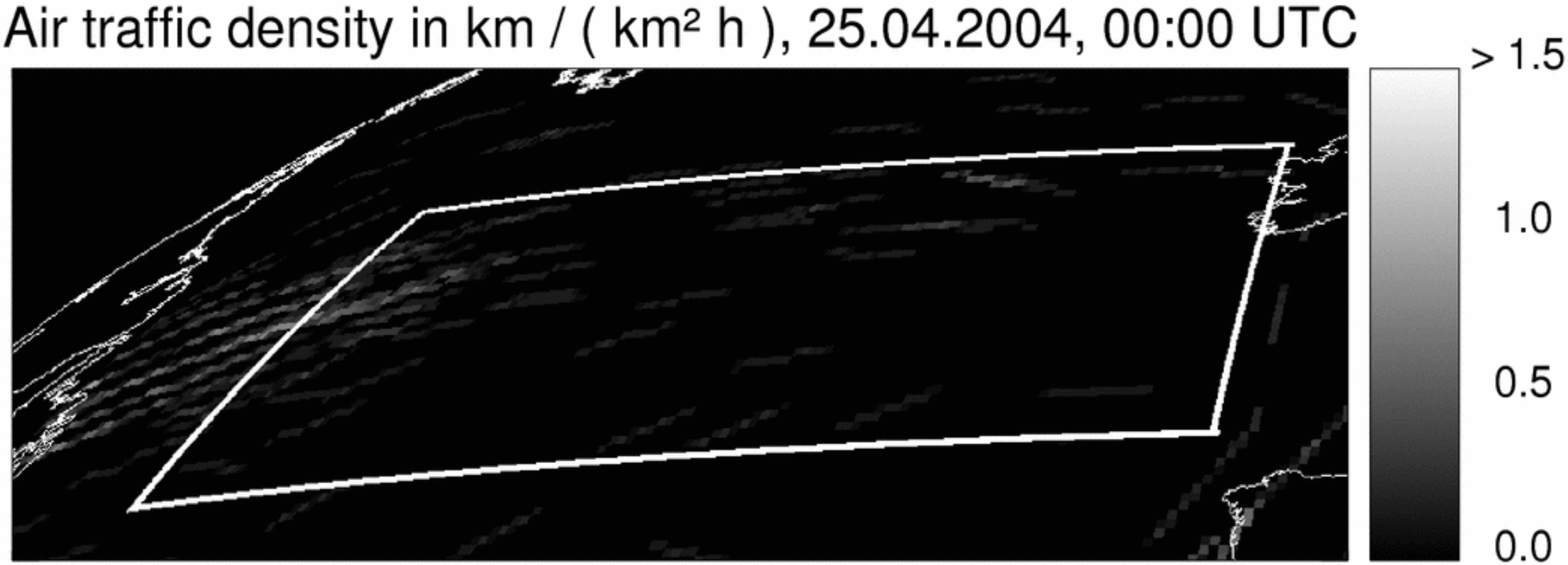
IPCC (1999): “Contrails tend to warm the Earth’s surface, similar to high clouds.”



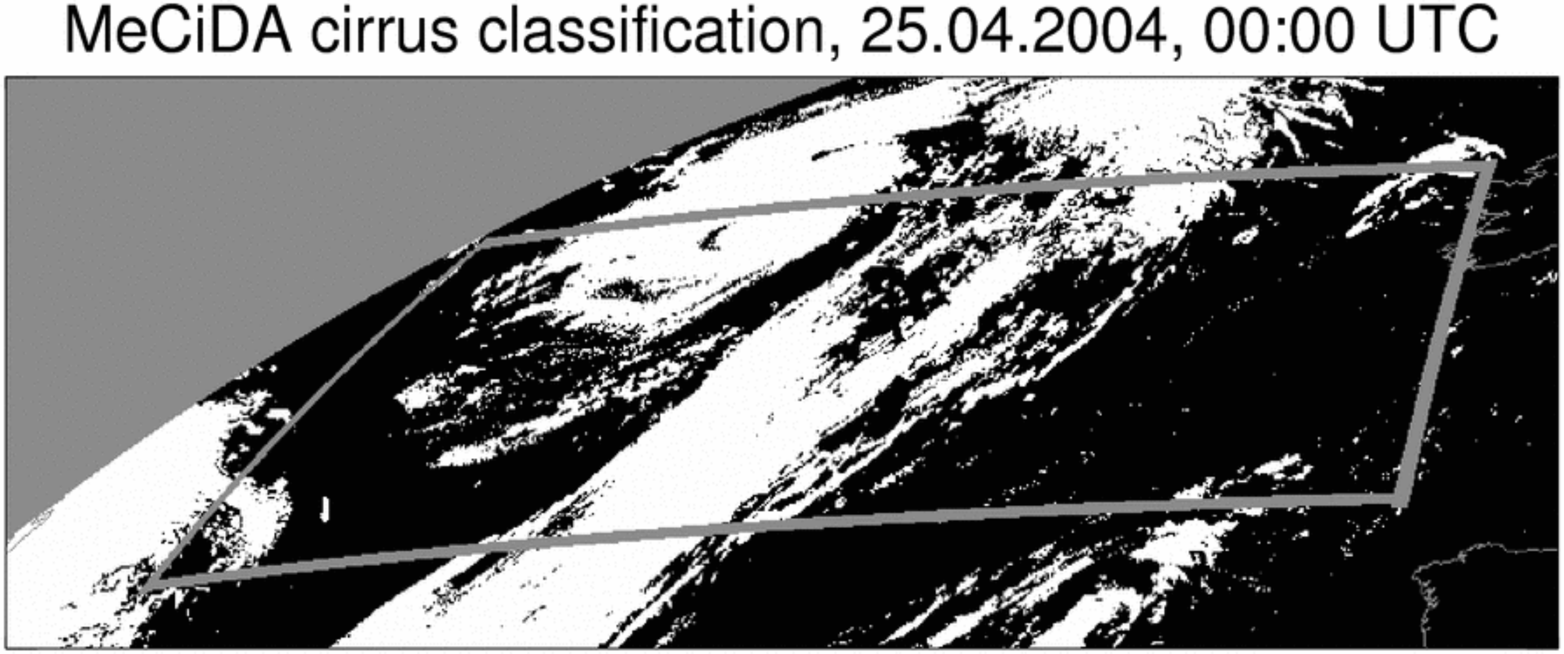
IPCC (1999): “Contrails tend to warm the Earth’s surface, similar to high clouds.”

Outline

1. Cover and RF from contrail cirrus
2. Surface temperature sensitivity


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

Meteosat SEVIRI IR data:


MeCiDA cirrus classification, 25.04.2004, 00:00 UTC

(Graf et al., GRL, 2012)

Contrail cirrus and RF_{LW} in North Atlantic region from Meteosat and model

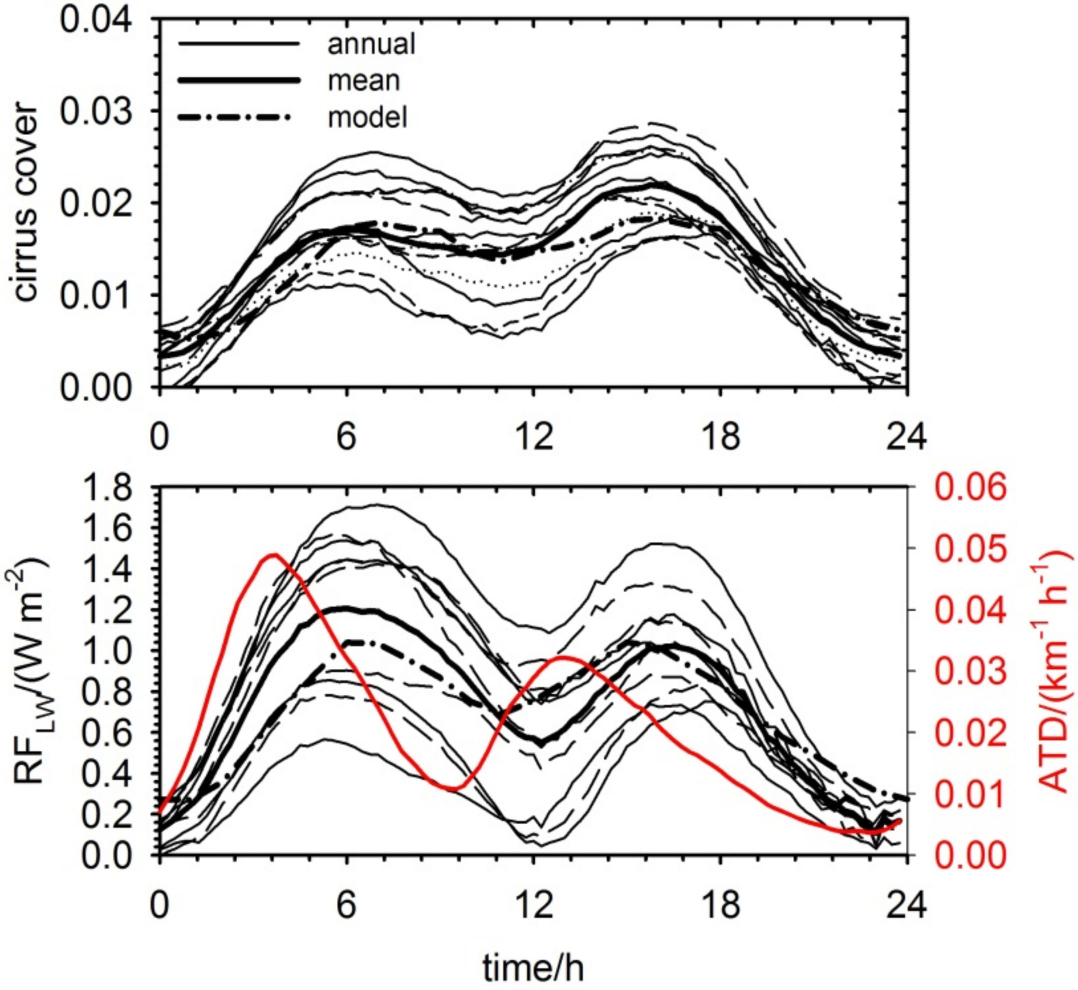
Red line: air traffic density (ATD)

Thin lines: 8 years of cirrus cover and OLR observations, RF from difference between North and South Atlantic domains

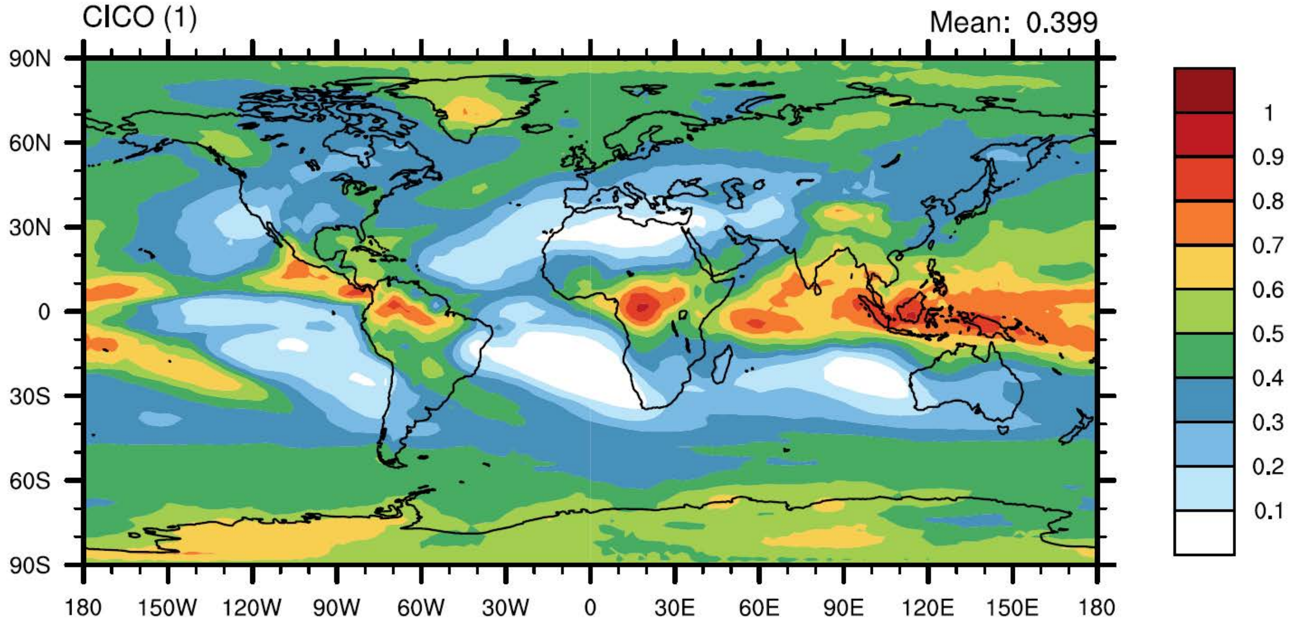
Thick lines: 8-year mean

Thick dash dotted: CoCiP/ECMWF Model result

[*Schumann and Graf*, JGR, 2013].



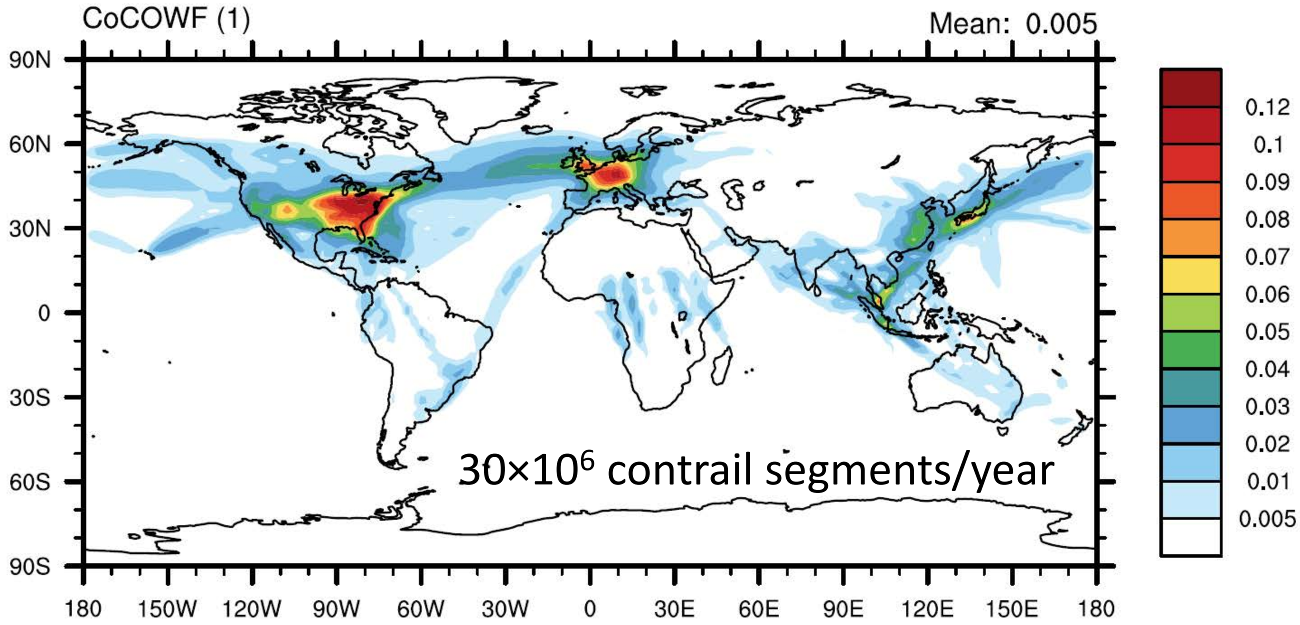
Cirrus and Contrails as simulated with CoCiP-CAM



Cirrus cover

and

Cover of contrails with $\tau > 0.1$

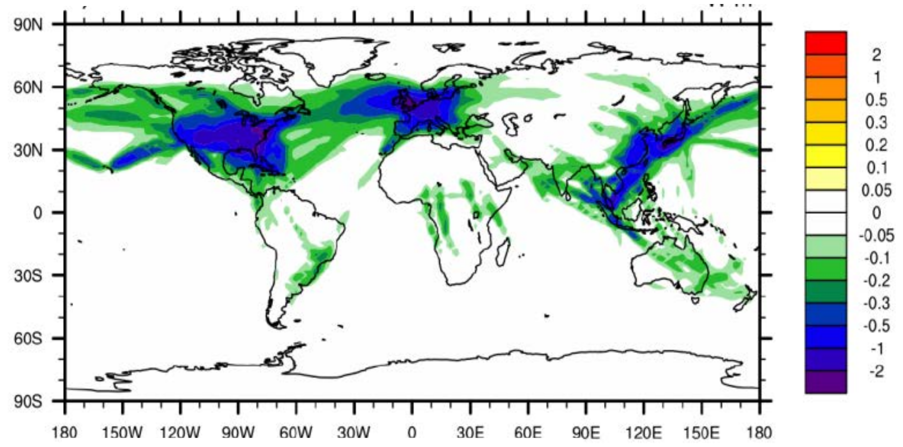


30×10^6 contrail segments/year

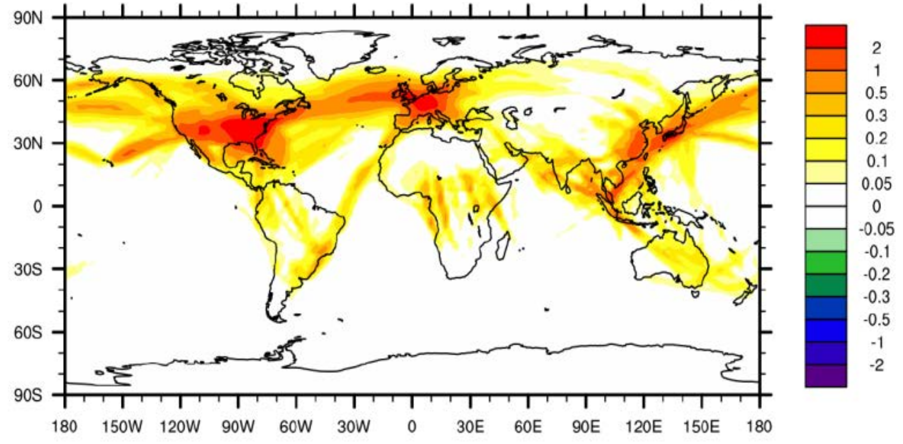
Schumann, Penner, Chen, Zhou, Graf (ACP, 2015)

Contrail Cirrus cause positive net Radiative Forcing with large negative and positive SW and LW contributions

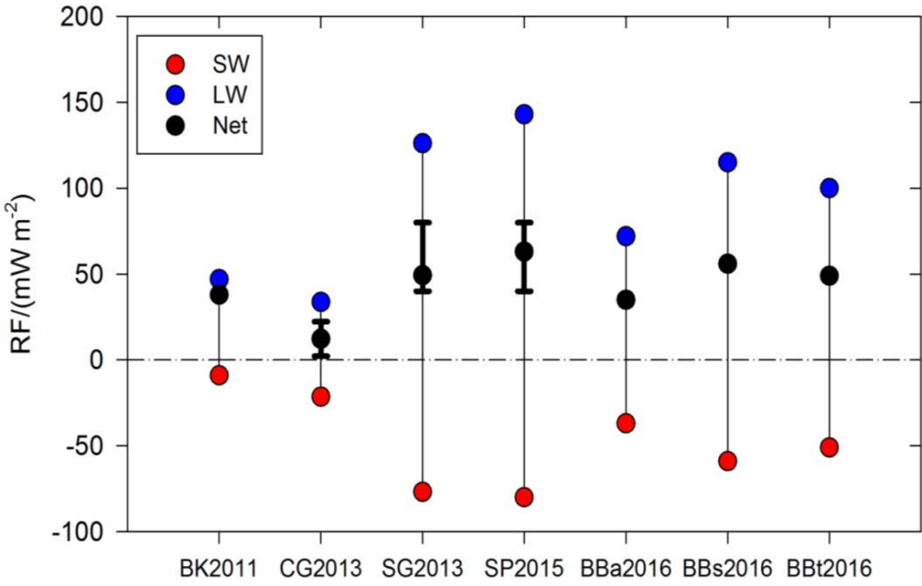
Shortwave (SW) $-0.079\ \mathrm{W\ m^{-2}}$



Longwave (LW) $0.140\ \mathrm{W\ m^{-2}}$



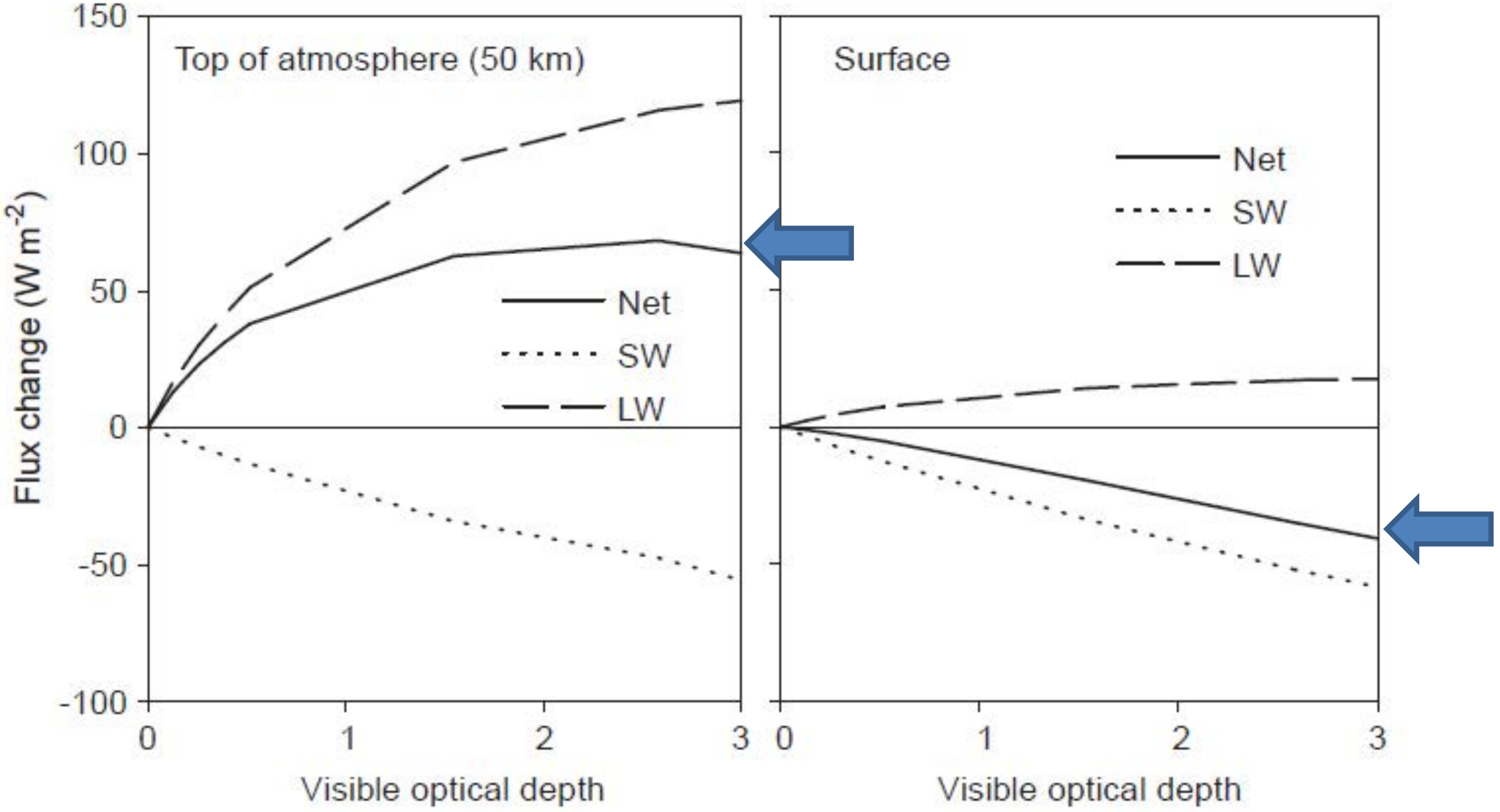
Schumann, Penner, Chen, Zhou, Graf (ACP, 2015)



Reference	Model/Traffic	Symbol
Burkhardt and Kärcher (2011)	ECHAM4 CCmod / AERO2K 2002	BK2011
Chen and Gettelman (2013)	CAM5-SD / AEDT 2006	CG2013
Schumann and Graf (2013)	Meteosat+ECMWF+CoCiP / 2006	SG2013
Schumann, Penner et al. (2015)	CAM+CoCiP/ 2006	SP2015
Bock and Burkhardt (2016)	ECHAM5 CCmod / AERO2K 2002	BBa2016
Bock and Burkhardt (2016)	ECHAM5 CCmod /AEDT 2006 slant	BBs2016
Bock and Burkhardt (2016)	ECHAM5 CCmod /AEDT 2006 track	BBt2016

Note: Contrail RF is larger than the RF from past aviation CO_2 emissions

Well known: Net RF of optically thin contrail cirrus is positive at TOA but negative at the Earth's surface



Meerkötter et al. (1999)

Thin ice clouds warm the Earth-atmosphere system,

but “ice clouds produce a cooling effect at Earth’s surface”

from CALIOP and libRadtran

(Hong et al., J. Clim., 2016)

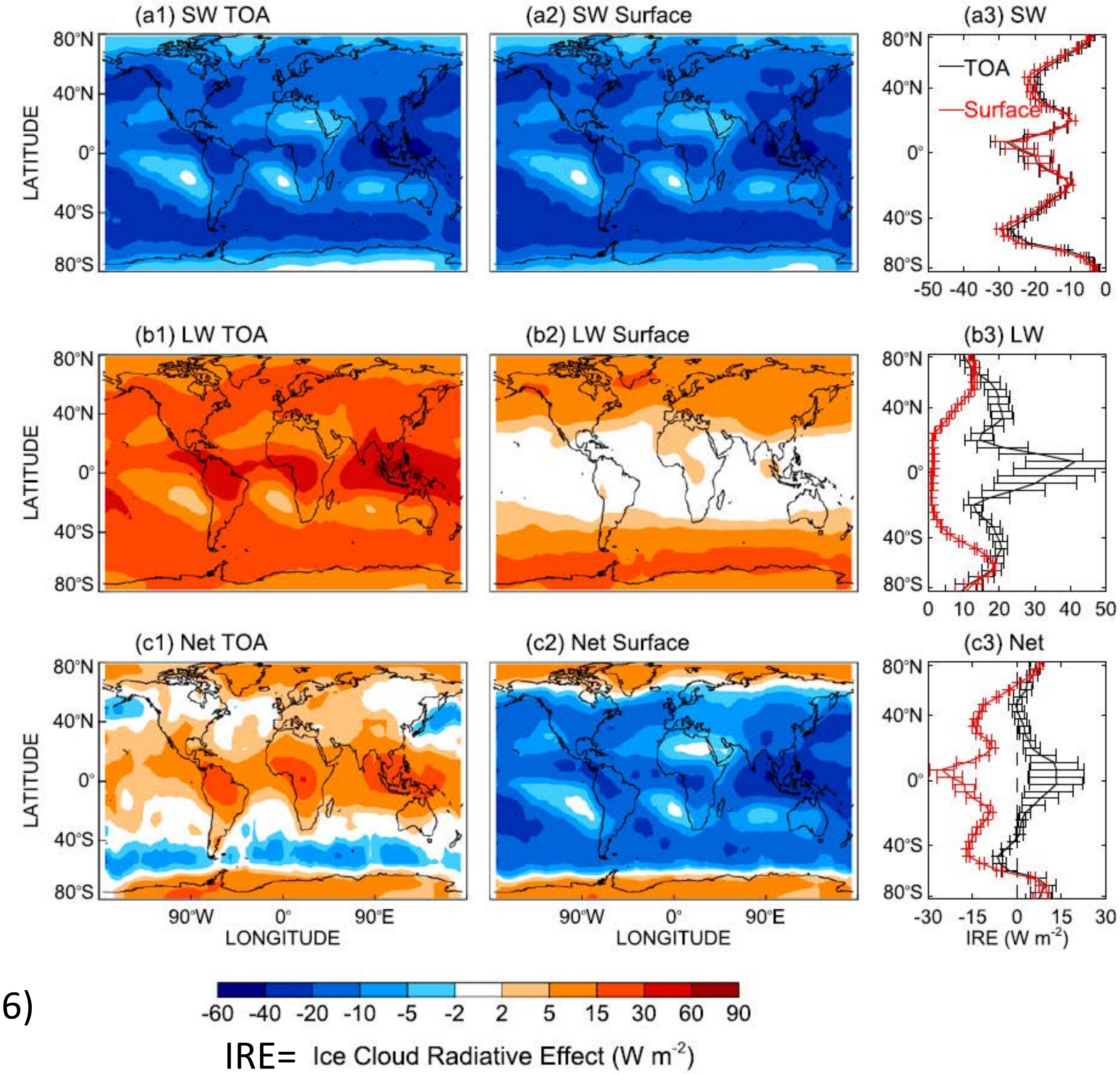
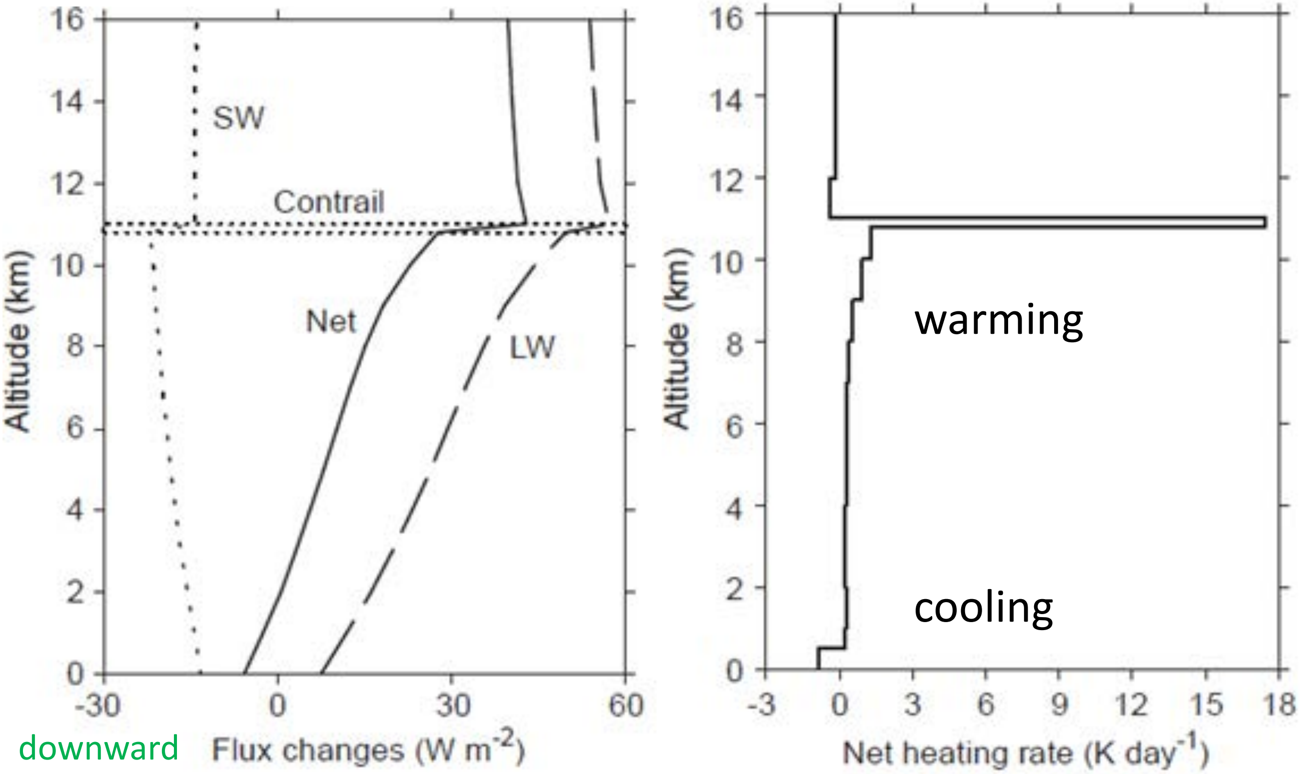


FIG. 2. Global distributions of (a) SW, (b) LW, and (c) net radiative effects of all ice clouds at TOA and the surface. (right) Zonal means of global ice cloud radiative effects at TOA and the surface for SW, LW, and net effects. Error bars represent the absolute value of ice cloud radiative effect differences between DARDAR and 2C-ICE.

Heating rate profiles

Even though the net RF may be positive at TOA:

Contrail cirrus may cool the surface.



Meerkötter et al. (1999)

$$H = \frac{\partial T}{\partial t} = -\frac{1}{\rho c_p}\frac{\partial F}{\partial z} = \frac{g}{c_p}\frac{\partial F}{\partial p}$$

How can the heat induced by cirrus in the upper troposphere reach the surface?

Mean Temperature Response in a GCM (ECHAM4) to (enhanced) Contrail Cirrus

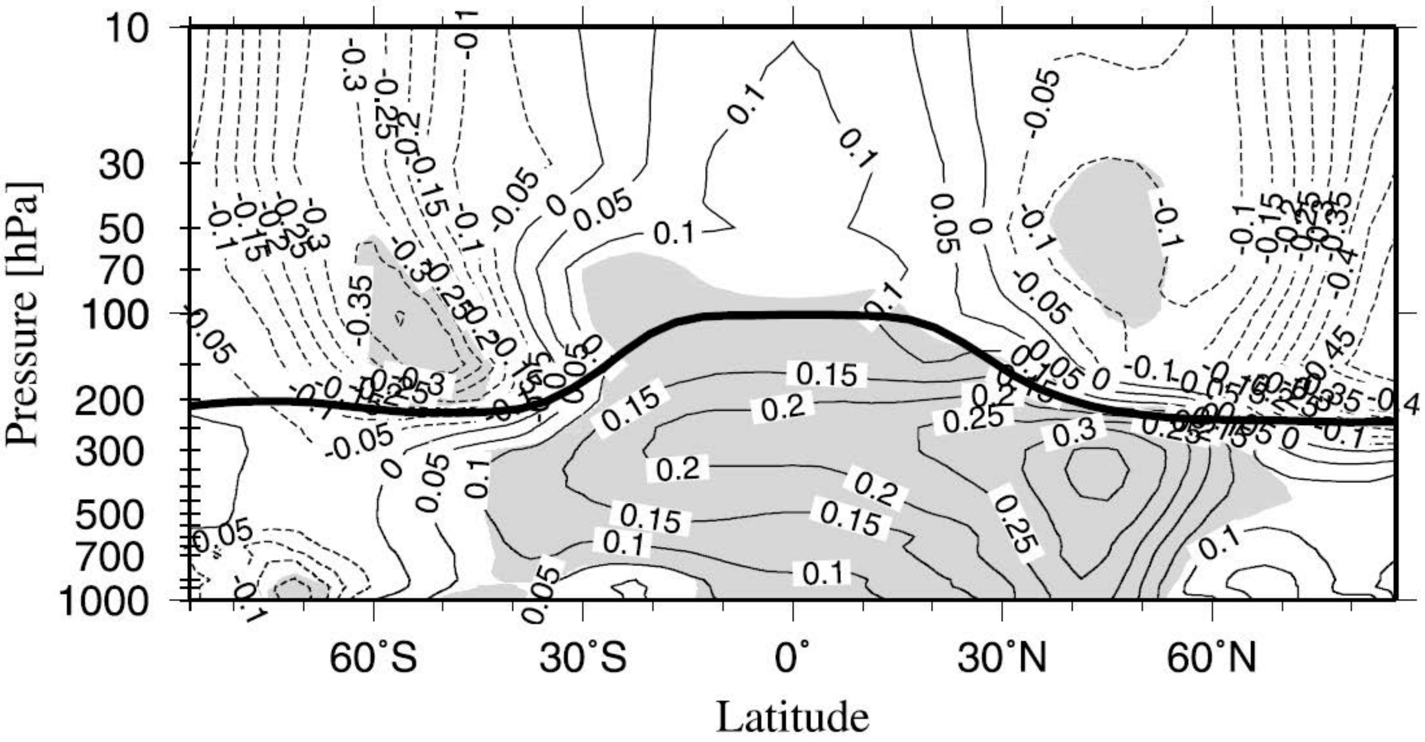


Figure 2. Zonal mean cross section of annual mean temperature response in the equilibrium climate simulation using enhanced contrail forcing. Thick line displays the tropopause. Shading indicates significance on a 95% level.

Efficacy
$e = \lambda_c / \lambda_{CO2}$
$\cong 0.6$

× 20

RF=0.2 W m^{-2}

(Ponater, Marquart, Sausen, Schumann, GRL, 2005)

Climate impact of contrail cirrus?

- RF = 0.05 (0.02 to 0.15) W m^{-2} (IPCC, 2013)
- $\Delta T = \lambda$ RF, an energy budget and feedback model (Dickinson, 1982, Hansen et al. 1981)
- $\lambda_{CO2} \cong 0.4\text{-}1.2$ K W^{-1} m^2 (IPCC, 2013)
- Efficacy $e = \lambda_c/\lambda_{CO2} \cong 0.3$ to 0.7 (Rap et al., 2010; Ponater et al., 2005)
- -> $\Delta T = 0.0024$ to 0.13 K
- **Global climate impact by contrails: Max/min ratio: factor 50!**

- Why is the efficacy for contrail cirrus so low?
- Are we sure that ΔT_s is positive?
- Can we expect larger regional changes?

- Here: Estimate of surface temperature sensitivity from a highly simplified 1d radiative-convective-diffusive model

Radiative-convective model with CO_2 and Cirrus

following Möller and Manabe (1961),
Manabe and Strickler (1964),
Manabe and Wetherald (1967),
Ramanathan and Coakley (1978)
Liou and Ou (1983),
Fu and Liou (1993)
Mayer and Kylling (2005)

Equilibrium response to CO_2 doubling and added cirrus without and with convective mixing

Temperature change for added cirrus in the radiative-convective-diffusive model in the mid-latitude summer atmosphere over adiabatic surface

Equilibrium temperature change

- for pure radiative equilibrium
- and with diffusive mixing

Contrail climate effect depends on how quickly heat gets transported from upper troposphere to the surface

(Schumann and Mayer, ACPD 2017)

Relaxation time scales determine how quick the cirrus-induced warming gets lost to space when cirrus is taken away

Time scales of hours to months

depending on

- Vertical scales
- Altitude
- Mixing

among others

(Schumann and Mayer, ACPD 2017)

Conclusions

- Upper troposphere heating induced by cirrus reaches the surface only for strong vertical mixing
- Contrail cirrus may cool the surface even for positive Radiative Forcing
- Because of more rapid cooling to space near the surface, SW surface cooling may dominate regionally where cirrus or contrails form, while LW warming may dominate at larger distances downwind

For details see Schumann and Mayer (ACPD, 2017)

To William B. Rossow

Congratulation for lead in setting up satellite cloud climatologies

All the best for your future

Do not stop looking for clouds

GEWEX 18th SSC meeting, Dakar, Senegal, January 2006

Temperature forcing approach

Model F: fast response $\Delta T_{F,d}$ to disturbance d

Model E: equilibrium climate change $\Delta T_{E,d}$ to d .

Preparations:

1) $\Delta T_{F,g,i}$, i= 1, 2, … m, for “ghost” forcings g_i, using the model F;

2) $\Delta T_{E,g,i}$, i= 1, 2, …. m , for same ghost forcings, using model E;

3) the “fast” solution $\Delta T_{F,d}$ of model F .

4) weighting coefficients α_i such that $\Delta T_{F,d} \approx \Delta \widetilde{T}_{F,d} = \sum_i \alpha_i \Delta T_{F,g,i}$

$$a_i = \left[\Delta T_{F,g,i} \Delta T_{F,g,j}\right]^{-1} \left[\Delta T_{F,g,i} \Delta T_{F,d}\right]$$

5) Then

$$\Delta \widetilde{T}_{E,d} = \Delta T_{F,d} + \sum_i \alpha_i \left(\Delta T_{E,g,i} - \Delta T_{F,g,i}\right)$$

Disturbances of mid-latitude summer standard atmosphere

First we consider 11 cases of ghost forcings (as in Hansen et al., 2005)

Instantaneous radiative heating rates H vs z.

Mid-latitude summer atmosphere

libRadtran, Fu&Liou molecular absorption, 2-stream solver (Mayer and Kylling, 2005)

Cirrus as in Fu (1996), Fu et al. (1998)

heating rate: $H = \frac{\partial T}{\partial t} = -\frac{1}{\rho c_p}\frac{\partial F}{\partial z} = \frac{g}{c_p}\frac{\partial F}{\partial p}$

Example: Ghost forcing in a “fast model” F with constant system properties and a “climate equilibrium model” E with T-mediated H_2O changes

Temperature change for ghost forcing disturbances g,i at 11 levels

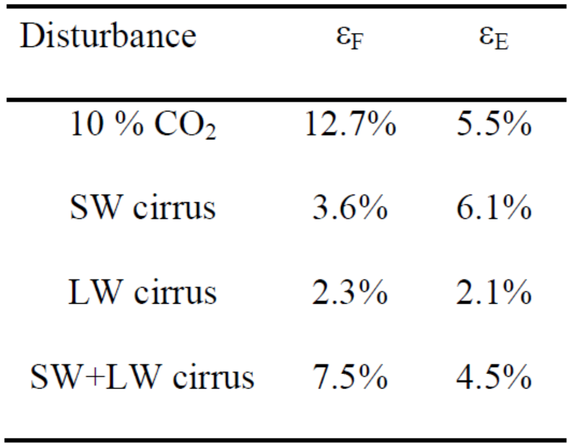
(a): for “fast” model F (radiative convective equilibrium for 1 W m^{-2} layer heating over adiabatic surface)

(b): “equilibrium” model E (with H_2O changes, i.e. constant relative humidity for changed temperature).

Example: TF results

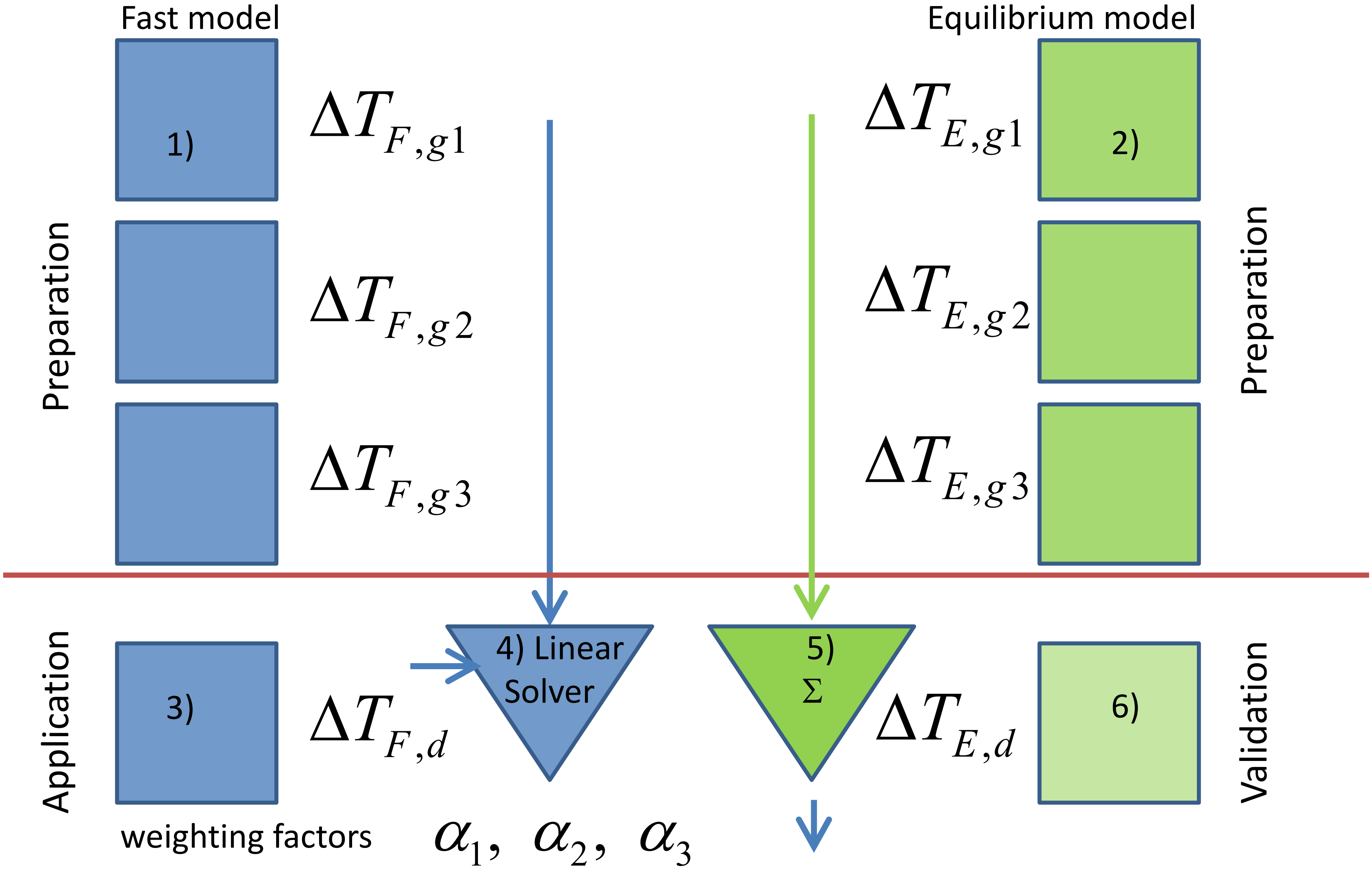
4 Examples of

- temperature forcing $T_{F,d}$ computed with fast model (F, full black)
- and ghost function approximation ($T_{F,d}$ with tilde, dashed black),
- equilibrium climate response $T_{E,d}$ for equilibrium model (E, full red)
- respective approximate solution ($T_{E,d}$ with tilde, dashed)



Disturbance	ε_F	ε_E
10 % CO_2	12.7%	5.5%
SW cirrus	3.6%	6.1%
LW cirrus	2.3%	2.1%
SW+LW cirrus	7.5%	4.5%

The TF-approach: temperature-mediated climate system changes



Fast model

Equilibrium model

Preparation

1) $\Delta T_{F,g1}$

$\Delta T_{F,g2}$

$\Delta T_{F,g3}$

$\Delta T_{E,g1}$ 2)

$\Delta T_{E,g2}$

$\Delta T_{E,g3}$

Preparation

Application

3) $\Delta T_{F,d}$

4) Linear Solver

5) Σ

$\Delta T_{E,d}$

6)

Validation

weighting factors $\alpha_1, \ \alpha_2, \ \alpha_3$

$$\Delta \widetilde{T}_{E,d} = \Delta T_{F,d} + \alpha_1 \Delta T_{E,g1} + \alpha_2 \Delta T_{E,g2} + \alpha_3 \Delta T_{E,g3}$$

ENDE

Foto: Andreas Schäfler