Radiative Effects of Contrails and Contrail Cirrus

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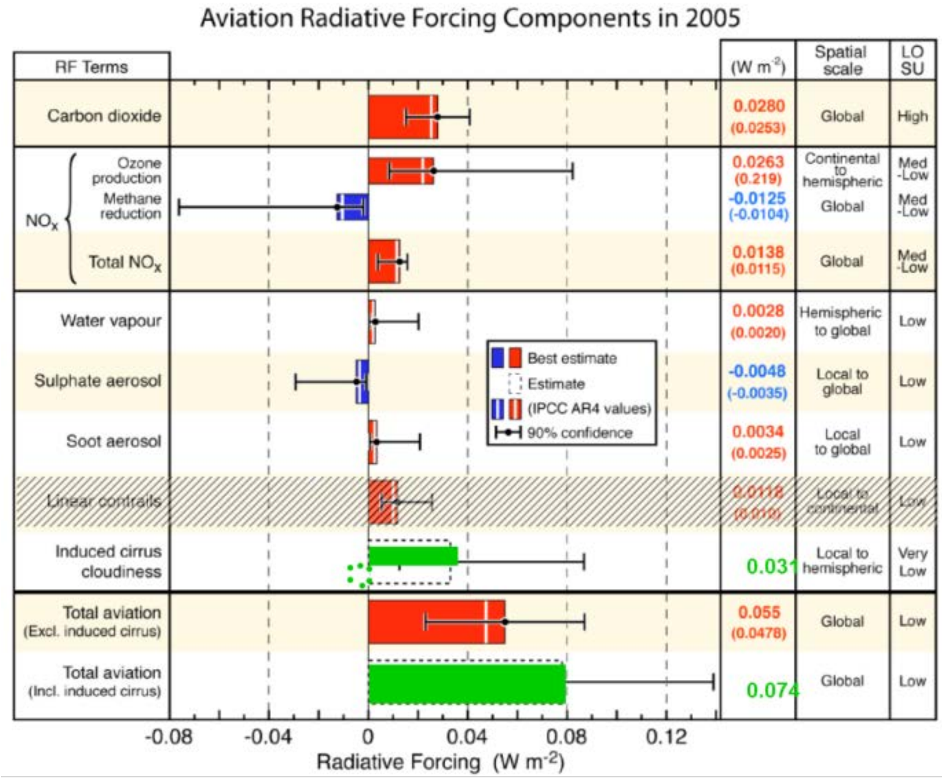
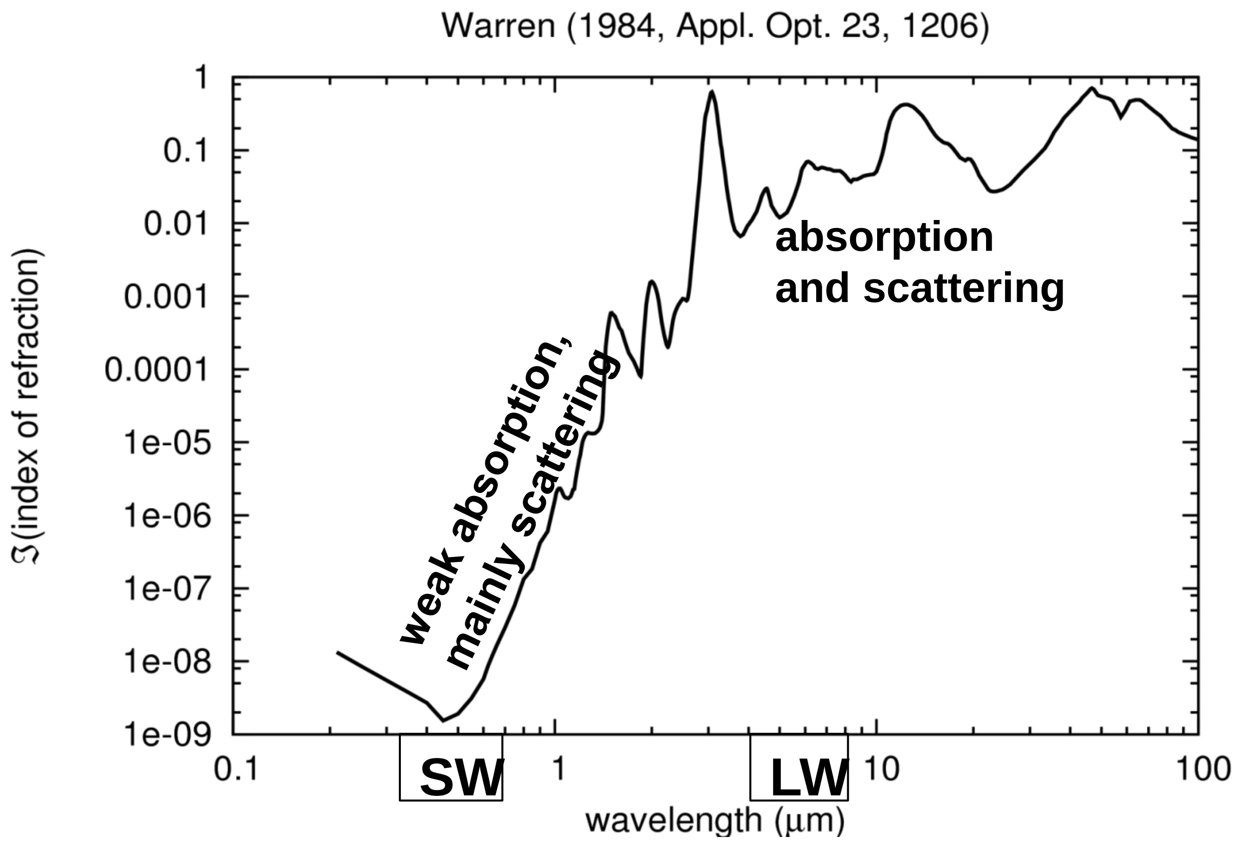
Two closely related riddles

1) Why has IPCC rated the level of scientific uncertainty as **fair** in 1999, when it considered aviation impacts on climate for the first time, but later as **low** for linear contrails or even **very low** for contrail cirrus?
2) How arises the difficulty to reduce the error bars on estimates of the radiative forcing (RF) of contrails and contrail cirrus although the underlying principles are rather simple?



Principles: Radiation interaction with ice



Note: Ice interacts with radiation ~300 times stronger than the same mass of water vapour at typical flight levels.

Principles of LW and SW forcing: Contrast

- LW forcing: “thermal” radiation depends strongly on temperature of the emitter (Stefan-Boltzmann T^4 law). Thus:
  - Strong LW forcing results from cold contrail embedded in warm background.
  - Forcing increases from pole to equator, from winter to summer, from cool night to warm day.

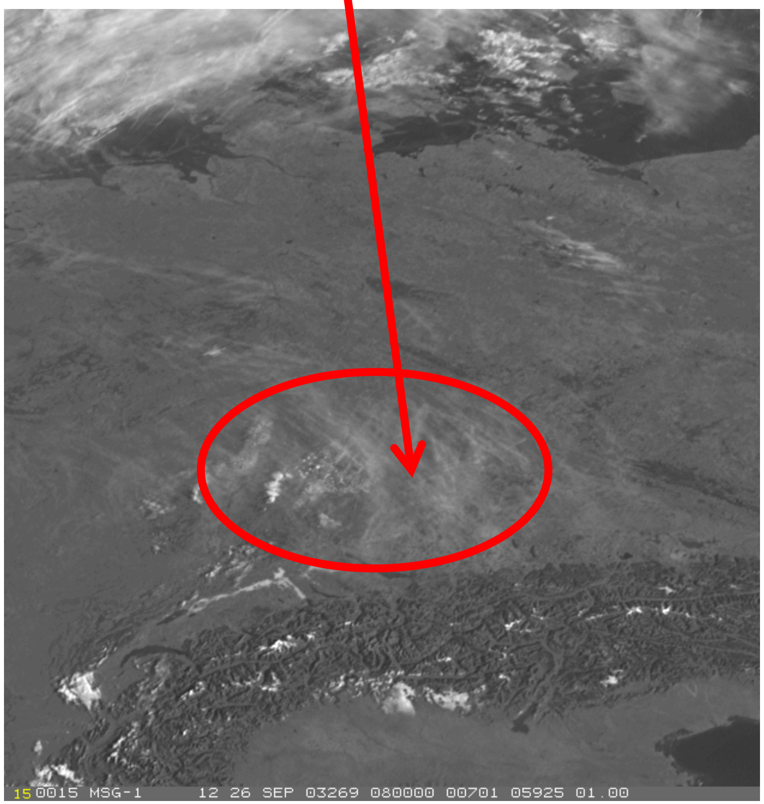
- SW forcing: “visible” radiation.
  - Strong SW forcing results from a visibility contrast.
  - Forcing increases from bright to dark background, from snow cover to open ocean water, from desert to forest areas, from cloudy to cloud free scenes.

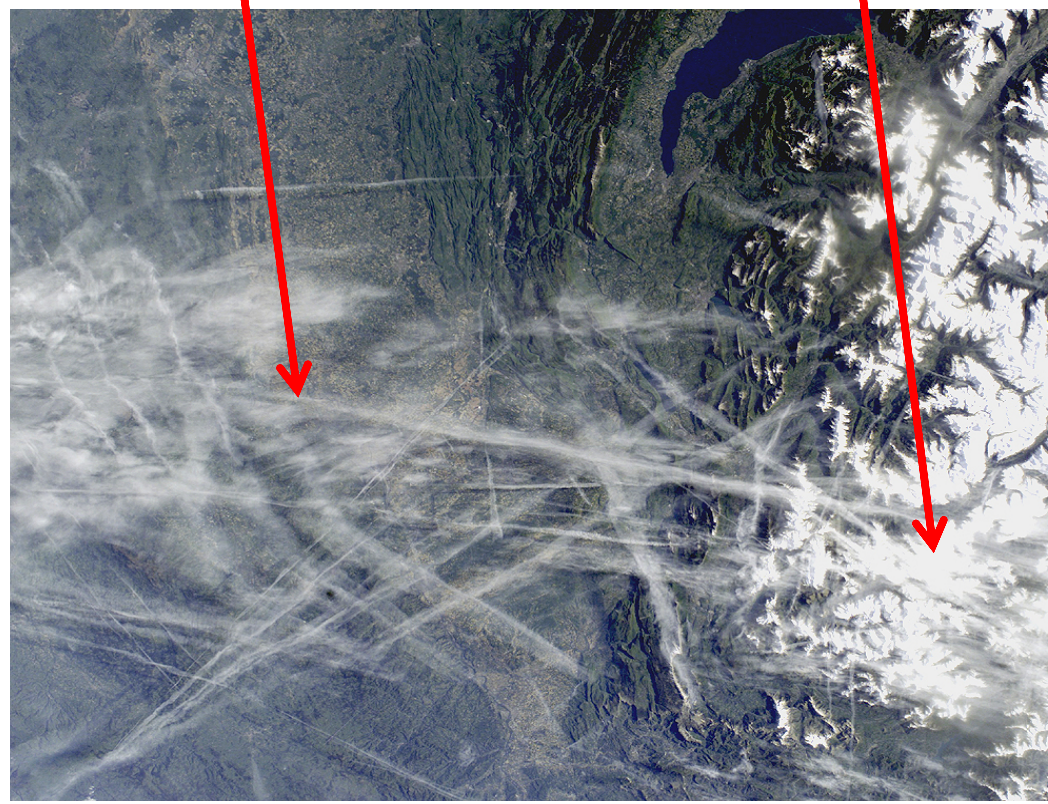
Examples

LW contrast: heating

SW contrast: cooling

no SW contrast



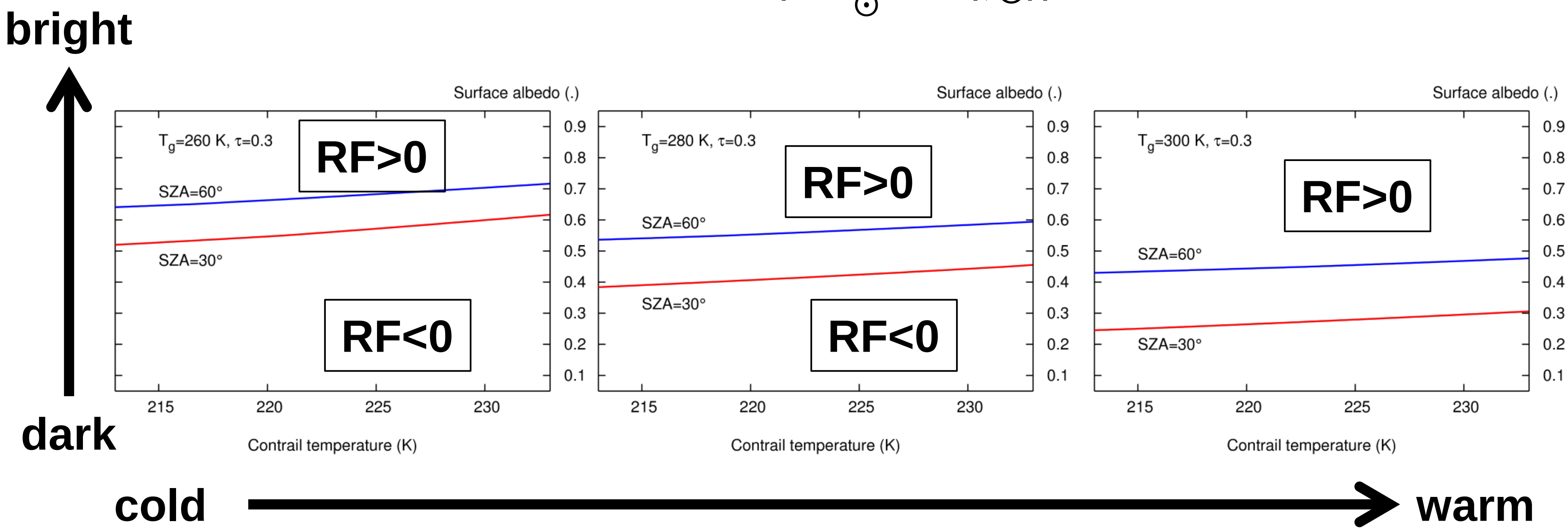


Radiative forcing at TOA

Temperature contrast: $F_{LW} = \sigma\varepsilon(\tau_a)\left({T_{bg}}^4 - {T_{con}}^4\right)$

Albedo (visibility) contrast: $F_{SW} = -S\Delta A[A_{bg}, R(\tau, g, \zeta_\odot)]$

with S: solar flux at the contrail ($\approx S_\odot \cos(\zeta_\odot)$).



RF mostly positive (warming). Exceptions: over very cold, but dark surfaces, at solar zenith angles of 60-80°, in a very humid atmosphere (low T-contrast), contrails with very small particles and low g-factor

Factors of influence: Instantaneous effect on flow of radiation

For the longwave:

- Background temperature and humidity;
- Contrail temperature and emissivity.

For the shortwave:

- Solar irradiance at the contrail (depends on solar zenith angle);
- Ground albedo (type and properties of the surface or underlying clouds);
- Reflectance of the contrail.

Contrail emissivity and reflectance are determined by

- ice content and thickness,
- ice crystal size and habit distribution.

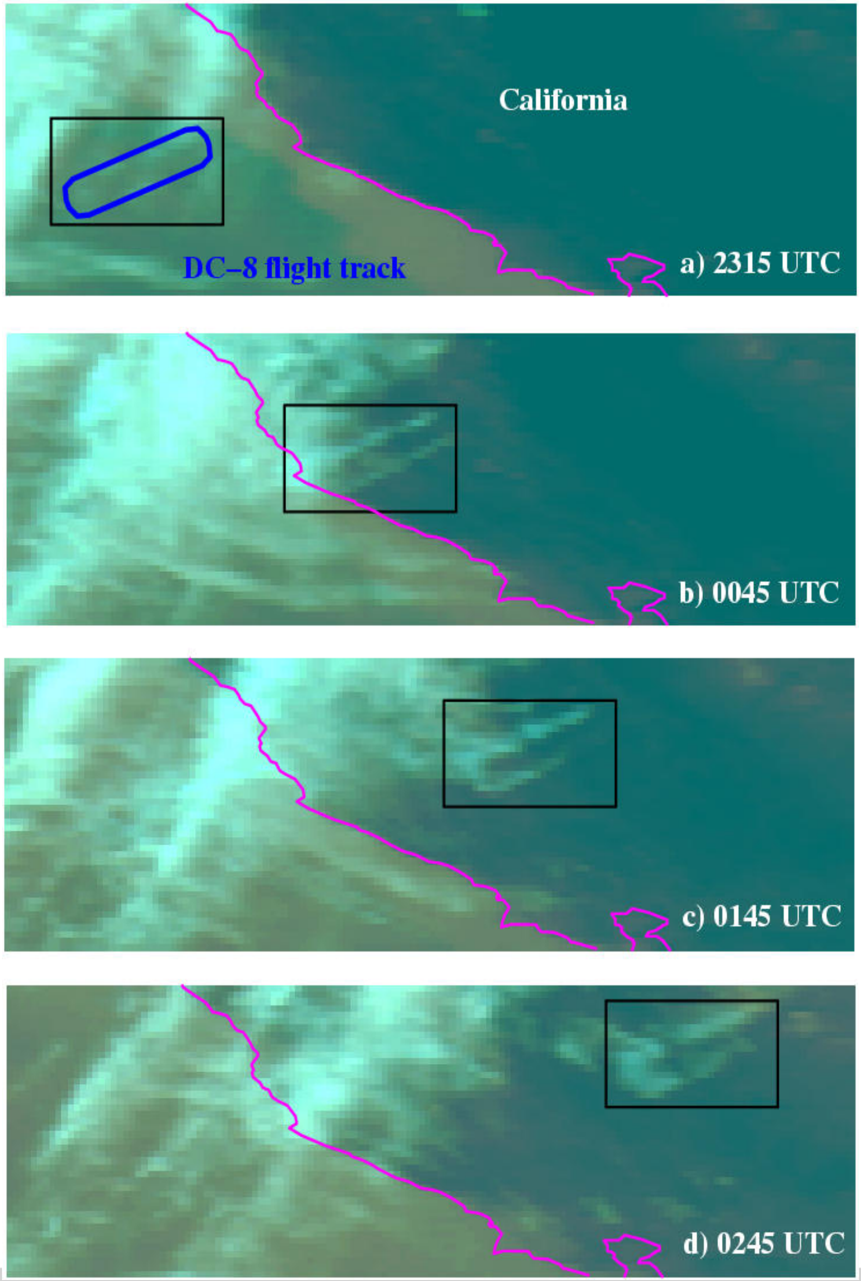
Factors of influence:
total effect on Earth's radiation energy budget

Moreover, the total impact of a contrail on Earth's energy depends on

- Contrail lifetime
- Contrail width over its lifetime (spreading rate)
- Contrail advection over its lifetime
- and the corresponding changes during lifetime of
  - its environment and
  - its microphysical and optical properties.

All factors of influence display natural variability, some span an enormous range.

Examples:
vastly different lifetimes



non-persistent contrail

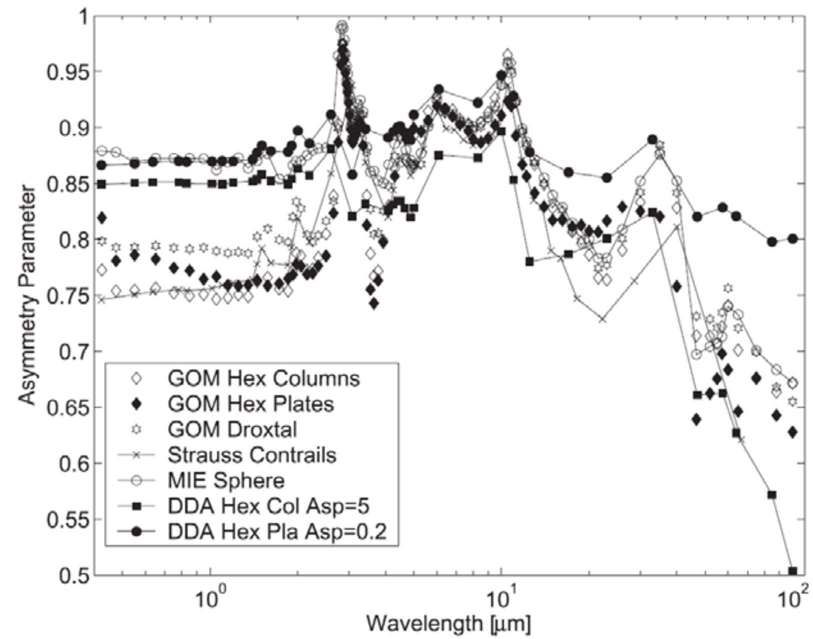
persistent contrail, duration > 17 hrs
(Minnis et al. 1998, SUCCESS)

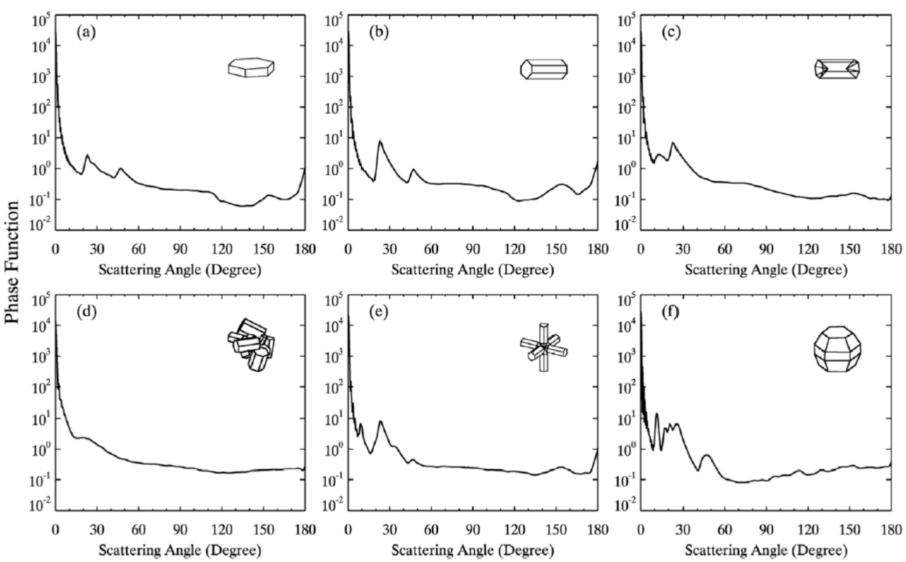
Examples: crystal habits, sizes, and contrail optics

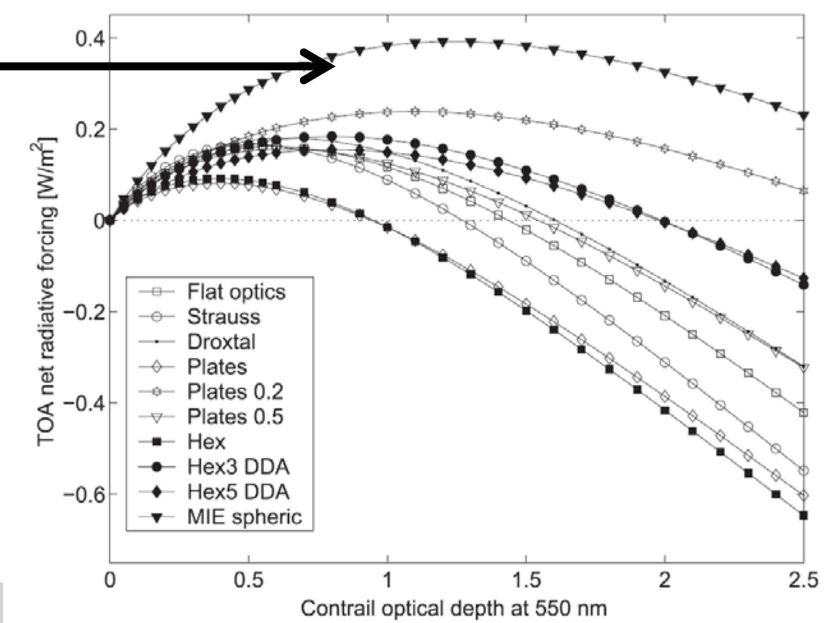
Results from Yang et al., 2010;

Markowicz and Witek, 2011;

Note that spherical particles have extreme RF

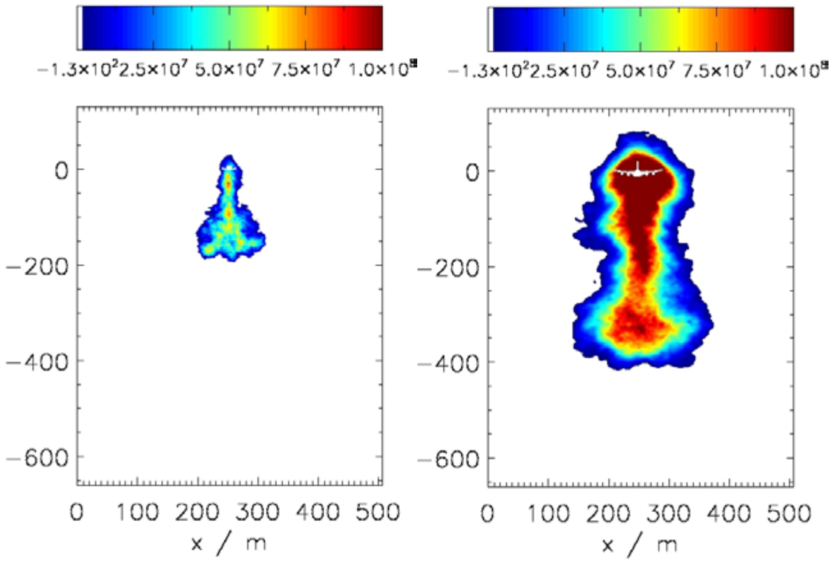






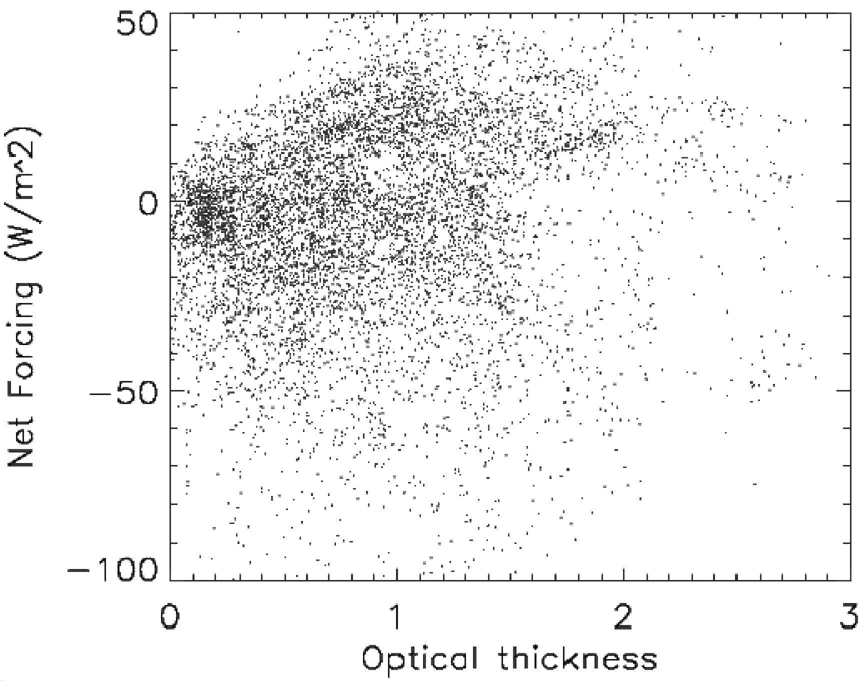
Examples: contrail thickness, IWC, optical thickness and net RF

Results from numerical simulation of contrails from two different A/C: CRJ vs. A380 (N. Görsch, 2012)



Results from satellite data inspection (M. Vazquez-Navarro, 2010):

4 months of data: large scatter
$\Rightarrow$ insufficient statistics



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Two closely related riddles, and their explanation

1) Why has IPCC rated the level of scientific uncertainty as **fair** in 1999, when it considered aviation impacts on climate for the first time, but later as **low** for linear contrails or even **very low** for contrail cirrus?
2) How arises the difficulty to reduce the error bars on estimates of the radiative forcing (RF) of contrails and contrail cirrus although the underlying principles are rather simple?

The large number and different nature of factors of influence and their partly enormous ranges make estimation of the radiative effect of single contrails considerably difficult.

Even more difficult is thus the determination of contrails' contribution to climate change, since this implies to consider all contrails under all their individual circumstances – obviously a hard statistical problem.

What do the error bars on the IPCC charts mean?

Error bars on IPCC charts represent 5-95% confidence ranges.

They express a belief of how good we can estimate the mean value.

They do not represent the natural variability.

The natural variability is much larger than the confidence range.

The non-negative confidence range expresses our belief that on the whole contrails contribute to climate warming.

In contrast, the natural variability includes cases with strong cooling and also much stronger heating than the upper end of the confidence range.

What do we want?

A very good estimate of the mean RF?

Need to reduce the confidence range: Increase the statistical basis of single values (observations). Note: $\sigma(\overline{RF}) = \sqrt{(\frac{Var(RF)}{N})}$

Or to reduce the climate effect of contrails?

Need to consider the whole variability in order to avoid those contrails that produce strong warming.

Needs as well to determine all the relevant parameters case-by-case.

Identify parameter combinations that lead to strong warming (i.e. distinguish between important and not-so-important parameters).

Example: Parametric RF model for contrail cirrus (Schumann et al. 2012)

Goal: simple formulae for the calculation of contrail RF using input information available from NWP model data (Regression).

Forward RT: libRadran runs with/without contrail.

- 4572 atmosphere/surface situations;
- random variation of 22 parameters in certain ranges:
  - water and ice clouds (position and properties); solar zenith angle; type, temperature and optical properties (BRDF) of surface;
  - contrail properties: depth, altitude, IWC, crystal habits.

In total: 36576 libRadran runs.

Example (continued): Important parameters

LW:

- OLR (outgoing longwave raditation, includes effects of background temperature and humidity profiles)
- Contrail temperature
- optical thickness of the contrail
- optical thickness of a cirrus above the contrail
- effective radius of contrail ice crystals

SW:

- optical thickness of the contrail
- solar zenith angle
- effective albedo of the background situation
- optical thickness of a cirrus above the contrail
- effective radius of contrail ice crystals

Example (continued): Parameterisation and application

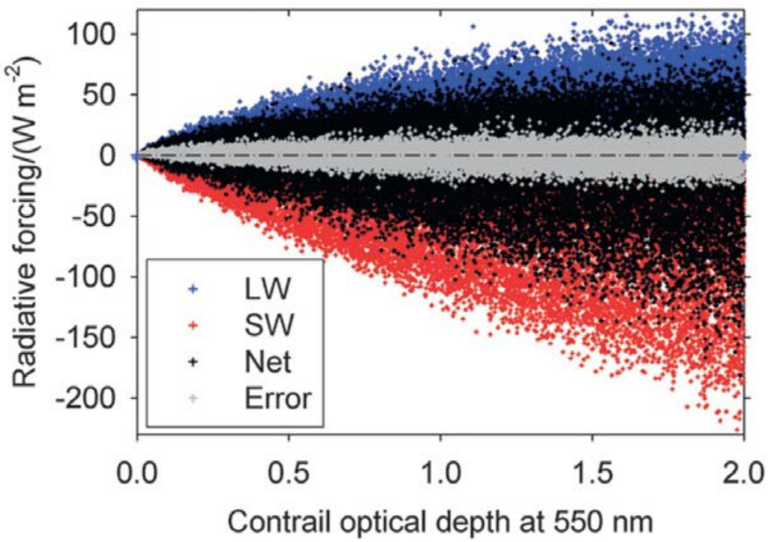
Parameterisation:

$$RF_{LW} = [OLR - k_T(T - T_0)]\{1 - \exp[-\delta_T F_{LW}(r_{\text{eff}})\tau]\}E_{LW}(\tau_c)$$

$$RF_{SW} = -SDR\left(t_A - A_{\text{eff}}\right)^2 \alpha_c\left(\mu, \tau, r_{\text{eff}}\right)E_{SW}(\mu, \tau_c)$$

Application:

Necessary input of the important parameters from NWP model and coupled contrail model (e.g. CoCiP, Schumann 2012).



Conclusions

- Radiative forcing of contrails and cc are in principle simple to understand, but
- SW and LW forcings depend on a large number of influential factors of various categories with partly wide natural variability:
    - contrail microphysical and optical properties
    - properties of the background atmosphere and ground
    - solar zenith angle (i.e. time and location)
    - large scale meteorology (wind, synoptic system).
- Error bars on IPCC charts do not reflect the natural variability.
- Need to decide whether we want to know the climatological mean more precisely or whether we rather want to avoid contrails' warming effects. Different approaches.
- A parameterisation for fast computation of contrail RF exists and can be used in contrail avoidance strategies, based on forecasts of actual cases (NWP and air traffic).