Climate impact of contrail cirrus

Marius Bickel, Michael Ponater, Lisa Bock, Ulrike Burkhardt, Svenja Reineke
What is contrail cirrus?

Linear contrails

Contrail cirrus

- Lose their line-shaped form
- Persist over many hours
- Spread over large areas
- Optical thin ($\tau$ mostly below 0.5)
- Hardly distinguishable from natural cirrus clouds
Global climate impact of contrail cirrus
Global climate impact of contrail cirrus

Measurements not available
Global climate impact of contrail cirrus

Measurements

- not available

Simulations

Temperature change simulations:
Direct determination of $\Delta T_{surf}$

- Computational expensive
- Coupled ocean needed
Global climate impact of contrail cirrus

Measurements
not available

Simulations

Temperature change simulations:
Direct determination of $\Delta T_{\text{surf}}$

- Computational expensive
- Coupled ocean needed

Radiative forcing simulations:
Determination of net radiative balance at top of atmosphere:

$RF$

+ $\rightarrow$ warming
- $\rightarrow$ cooling
Global climate impact of contrail cirrus

Measurements

not available

Simulations

Temperature change simulations:
Direct determination of \( \Delta T_{\text{surf}} \)

- Computational expensive
- Coupled ocean needed

Radiative forcing simulations:
Determination of net radiative balance at top of atmosphere:

\[ \text{RF} \]

+ \( \rightarrow \) warming
- \( \rightarrow \) cooling

\[ \Delta T_{\text{surf}} = \lambda \cdot \text{RF} \]

\( \lambda \): climate sensitivity \([\text{Wm}^{-2}\text{K}^{-1}]\)
Global climate impact of contrail cirrus

- CO$_2$
- Ozone (fast)
- Methane
- Ozone (PMO)
- Total NO$_x$
- Water vapour
- Sulphate aerosol (direct)
- Soot aerosol (direct)
- Aerosol (incl. clouds)
- Line-shaped contrails
- Induced cirrus
- Contrail cirrus

RF [mW m$^{-2}$]

Symbols:
- ○ Søvde et al. (2014): EMAC, multi-model mean
- × Righi et al. (2013): reference case, parameter span
- ☆ Voigt et al. (2011)
- △ Burkhardt and Kärcher (2011)
- ○ Schumann and Graf (2013)
- ◆ Schumann et al. (2015)
- ▼ Bock and Burkhardt (2016)
Global climate impact of contrail cirrus

- CO₂
- Ozone (fast)
- Methane
- Ozone (PMO)
- Total NOₓ
- Water vapour
- Sulphate aerosol (direct)
- Soot aerosol (direct)
- Aerosol (incl. clouds)
- Line-shaped contrails
- Induced cirrus
- Contrail cirrus

RF [mW m⁻²]

- Søvde et al. (2014): EMAC, multi-model mean
- Righi et al. (2013): reference case, parameter span
- Voigt et al. (2011)
- Burkhardt and Kärcher (2011)
- Schumann and Graf (2013)
- Schumann et al. (2015)
- Bock and Burkhardt (2016)
Global climate impact of contrail cirrus

\[ \Delta T_{\text{surf}} = \lambda \cdot RF \]

\( \lambda \): climate sensitivity \([\text{Wm}^{-2}\text{K}^{-1}]\)
Global climate impact of contrail cirrus

\[ \Delta T_{\text{surf}} = \lambda \cdot \text{RF} \]

\( \lambda \): climate sensitivity \([\text{Wm}^{-2}\text{K}^{-1}]\)

but: \( \lambda \) may be dependent on forcing

Grewe et al., 2017
Radiative Forcings, Rapid Adjustments and Slow Feedbacks

- Radiative Forcings (RF)
- Rapid Adjustments
- Slow Feedbacks

ΔR: Radiative Forcing
ΔT: Temperature Change

IRF: Initial Radiative Forcing
ERF: Equilibrium Radiative Forcing

λ: Feedback Parameter

~ month
~ decades
Radiative Forcings, Rapid Adjustments und Slow Feedbacks

- Rapid adjustments
- Slow feedbacks

\[ \Delta R \]
\[ \Delta T_{\text{equilibrium}} \]
\[ \Delta T_{\text{surface}} \]
\[ \lambda \]

\(~ \text{month}~ \) \(~ \text{decades}~ \)
Radiative Forcings, Rapid Adjustments und Slow Feedbacks

\[ \Delta T_{\text{surf}} = r \cdot \lambda \cdot RF \]
\[ \Delta T_{\text{surf}} = \lambda \cdot ERF \]

(after the ERF framework)

\( r \) : efficacy

\( \lambda \)

~ month  
~ decades

In the diagram, the relationship between \( \Delta T_{\text{surf}} \) and \( \Delta R \) is illustrated, showing the impact of radiative forcings on surface temperature changes over different timescales.
Modell Setup

- ECHAM5 climate model, resolution: 2.8° (horizontal), 600m (vertical)
- Contrail cirrus parametrization: Bock und Burkhardt (2016)
  - two-moment scheme (Ice water content und Ice crystal number concentration)
- AEDT 2050 air traffic data set (Water vapor emissions and Air traffic density)

Conventional RF simulations:
- Calculation of RF within one simulation (radiation double calling)
- ~5 years / simulation

ERF simulations:
- FSST method
- 2 independent simulations: Reference und Experiment
- ~30 years / simulation

IPCC, 2008
Air traffic and Radiative Forcing

Radiative Forcing:

2006: 56 mW m\(^{-2}\) (Bock and Burkhardt, 2016)

2050: 169 mW m\(^{-2}\)

Air traffic (Wilkerson et al., 2011):

2006: 38.2 \(\cdot\) 10\(^9\) km / year (AEDT 2006)

2050: 155.8 \(\cdot\) 10\(^9\) km / year (AEDT 2050)
RF simulations with scaled air traffic
RF simulations with scaled air traffic

![Graph showing RF contrail cirrus and ERF contrail cirrus forcing as a function of multiple of air traffic.](image-url)
RF simulations with scaled air traffic

![Graph showing CO₂ increase and RF forcing with scaled air traffic]

Key:
- RF contrail cirrus
- ERF contrail cirrus
- RF CO₂

**Axes:**
- Y-axis: Forcing [mW m⁻²]
- X-axis: Multiple of air traffic

**CO₂ increase [ppm]:**
- +25.5
- +37
- +42
- +45

Note: The graph illustrates the impact of increased contrail cirrus on CO₂ increase and RF forcing with scaled air traffic.
RF simulations with scaled air traffic

![Graph showing the relationship between CO₂ increase [ppm] and multiple of air traffic. The graph compares RF contrail cirrus, ERF contrail cirrus, RF CO₂, and ERF CO₂ against the multiple of air traffic.]
RF simulations with scaled air traffic

- Saturation in regions with high air traffic density
- Scaling of air traffic is needed to yield statistical significant results
- ERF of contrail cirrus is substantially reduced compared to its conventional RF
- The reduction of ERF is much weaker for a CO\textsubscript{2} forcing
RF simulations with scaled air traffic

- Saturation in regions with high air traffic density
- Scaling of air traffic is needed to yield statistical significant results
- ERF of contrail cirrus is substantially reduced compared to its conventional RF
- The reduction of ERF is much weaker for a CO$_2$ forcing

→ Why is the ERF of contrail cirrus reduced???
Feedback analysis: Contrail cirrus rapid adjustments

![Graph showing rapid adjustments](image)
Feedback analysis: Contrail cirrus rapid adjustments

Change at 200 hPa: $+3.6\%$ $-1.3\%$

Contrail cirrus cover change (95 % conf.) | 12 x air traffic | 25 years

Natural cloud cover change (95 % conf.) | 12 x air traffic | 25 years

$\rightarrow$ Contrail cirrus growth at the expense of natural cirrus cover
Feedback analysis: Contrail cirrus rapid adjustments

Temperature change (99 % conf.) | 12 × air traffic | 25 years

- positive stratospheric temperature adjustment
- negative lapse rate adjustment
Feedback analysis: Comparison with CO₂ experiment

- CO₂ (+45 ppm CO₂, ΔT = +0.025 K, 25 years)
- contrail cirrus (12 × air traffic, ΔT = +0.012 K, 25 years)

Forcing [W m⁻²]

- albedo
- cloud
- H₂O
- lapse rate
- planck
- total
Climate impact of aviation

### Global Aviation Effective Radiative Forcing (ERF) Terms (1940 to 2018)

<table>
<thead>
<tr>
<th>Term</th>
<th>ERF (mW/m²)</th>
<th>RF (mW/m²)</th>
<th>ERF/RF</th>
<th>Conf. levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrail cirrus in high-humidity regions</td>
<td>57.4 (17, 98)</td>
<td>111.4 (33, 169)</td>
<td>0.42</td>
<td>Low</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂) emissions</td>
<td>34.3 (28, 40)</td>
<td>34.3 (31, 28)</td>
<td>1.0</td>
<td>High</td>
</tr>
<tr>
<td>Nitrogen oxide (NOₓ) emissions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-term ozone increase</td>
<td>49.3 (32, 76)</td>
<td>38.0 (23, 56)</td>
<td>1.37</td>
<td>Med.</td>
</tr>
<tr>
<td>Long-term ozone decrease</td>
<td>-10.5 (-20, -7.4)</td>
<td>-9.0 (-17, -6.3)</td>
<td>1.18</td>
<td>Low</td>
</tr>
<tr>
<td>Methane decrease</td>
<td>-21.2 (-40, -16)</td>
<td>-17.9 (-34, -13)</td>
<td>1.18</td>
<td>Med.</td>
</tr>
<tr>
<td>Stratospheric water vapor decrease</td>
<td>-3.2 (-6.0, -2.2)</td>
<td>-2.7 (-5.6, -1.9)</td>
<td>1.18</td>
<td>Low</td>
</tr>
<tr>
<td>Net for NOₓ emissions</td>
<td>17.5 (6.9, 29)</td>
<td>8.2 (-4.8, 16)</td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Water vapor emissions in the stratosphere</td>
<td>2.0 (0.8, 3.2)</td>
<td>2.0 (0.8, 3.2)</td>
<td>[1]</td>
<td>Med.</td>
</tr>
<tr>
<td>Aerosol-radiation interactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-from soot emissions</td>
<td>0.94 (0.1, 4.9)</td>
<td>0.94 (0.1, 4.9)</td>
<td>[1]</td>
<td>Low</td>
</tr>
<tr>
<td>-from sulfur emissions</td>
<td>-7.4 (-10, -2.6)</td>
<td>-7.4 (-10, -2.6)</td>
<td>[1]</td>
<td>Low</td>
</tr>
<tr>
<td>Aerosol-cloud interactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-from sulfur emissions</td>
<td>No best estimates</td>
<td>No best estimates</td>
<td></td>
<td>Very low</td>
</tr>
<tr>
<td>-from soot emissions</td>
<td>No best estimates</td>
<td>No best estimates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net aviation (Non-CO₂ terms)</td>
<td>66.6 (21, 111)</td>
<td>114.8 (35, 164)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net aviation (All terms)</td>
<td>100.9 (55, 165)</td>
<td>149.1 (70, 229)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lee et al., 2020
## Climate impact of aviation

### Global Aviation Effective Radiative Forcing (ERF) Terms (1940 to 2018)

<table>
<thead>
<tr>
<th>Source</th>
<th>ERF (W m⁻²)</th>
<th>RF (W m⁻²)</th>
<th>ERF Change (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrail cirrus in high-humidity regions</td>
<td>57.4 (17, 98)</td>
<td>111.4 (33, 169)</td>
<td>0.2</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂) emissions</td>
<td>34.3 (29, 46)</td>
<td>34.3 (31, 58)</td>
<td>1.0</td>
</tr>
<tr>
<td>Nitrogen oxide (NO₂) emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-term ozone increase</td>
<td>-49.3 (-32, 76)</td>
<td>38.0 (23, 56)</td>
<td>1.37</td>
</tr>
<tr>
<td>Long-term ozone decrease</td>
<td>-10.5 (-20, -7.4)</td>
<td>-9.0 (-17, -6.3)</td>
<td>1.16</td>
</tr>
<tr>
<td>Methane decrease</td>
<td>-21.2 (-40, -15)</td>
<td>-17.9 (-34, -15)</td>
<td>1.16</td>
</tr>
<tr>
<td>Stratospheric water vapor decrease</td>
<td>-3.2 (-6.0, -2.2)</td>
<td>-2.7 (-5.6, -1.9)</td>
<td>1.16</td>
</tr>
<tr>
<td>Nitrogen for NOX emissions</td>
<td>17.5 (6.9, 29)</td>
<td>8.2 (-4.8, 16)</td>
<td>---</td>
</tr>
<tr>
<td>Water vapor emissions in the stratosphere</td>
<td>2.0 (0.8, 3.2)</td>
<td>2.0 (0.8, 3.2)</td>
<td>[1]</td>
</tr>
<tr>
<td>Aerosol-radiation interactions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- from soot emissions</td>
<td>0.94 (0.1, 4.9)</td>
<td>0.94 (0.1, 4.9)</td>
<td>[1]</td>
</tr>
<tr>
<td>- from sulfur emissions</td>
<td>-7.4 (-10, -2.6)</td>
<td>-7.4 (-10, -2.6)</td>
<td>[1]</td>
</tr>
<tr>
<td>Aerosol-cloud interactions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- from sulfur emissions</td>
<td>No best estimates</td>
<td>No best estimates</td>
<td>---</td>
</tr>
<tr>
<td>- from soot emissions</td>
<td>No best estimates</td>
<td>No best estimates</td>
<td>---</td>
</tr>
<tr>
<td>Net aviation (Non-CO₂ terms)</td>
<td>66.8 (21, 111)</td>
<td>114.8 (35, 164)</td>
<td>---</td>
</tr>
<tr>
<td>Net aviation (All terms)</td>
<td>100.9 (55, 168)</td>
<td>149.1 (70, 229)</td>
<td>---</td>
</tr>
</tbody>
</table>

Lee et al., 2020
Climate impact of aviation

Lee et al., 2020
Heating rate profile of contrail cirrus
Climate impact of aviation

However, not the end…

$$\Delta T_{surf} = r \cdot \lambda \cdot ERF$$

After the ERF framework $r$ is supposed to be 1
Climate impact of aviation

However, not the end…

\[ \Delta T_{\text{surf}} = r \cdot \lambda \cdot \text{ERF} \]

After the ERF framework \( r \) is supposed to be 1

**But:** Literature shows that \( r \) is not 1 for certain forcing agents (Shine et al. 2012; Marvel et al., 2016)

→ Direct simulations of the surface temperature response are needed to directly determine \( r \) and thus confirm the validity of the ERF framework for contrail cirrus
Conclusions

• ERF of contrail cirrus is substantially reduced compared to its conventional RF

• Feedback analysis shows that a negative natural cloud adjustment due to a loss of natural cirrus cover is the main reason for this reduction

• The reduction of ERF is much weaker for a CO$_2$ forcing

• These results suggest a reduced climate impact of contrail cirrus compared to what conventional RF estimates suggest

• But: Direct simulations of surface temperature change are needed to confirm the actual impact of the reduced ERF for contrail cirrus