Estimating the Climate Efficacy of Contrail Cirrus on Surface Temperature

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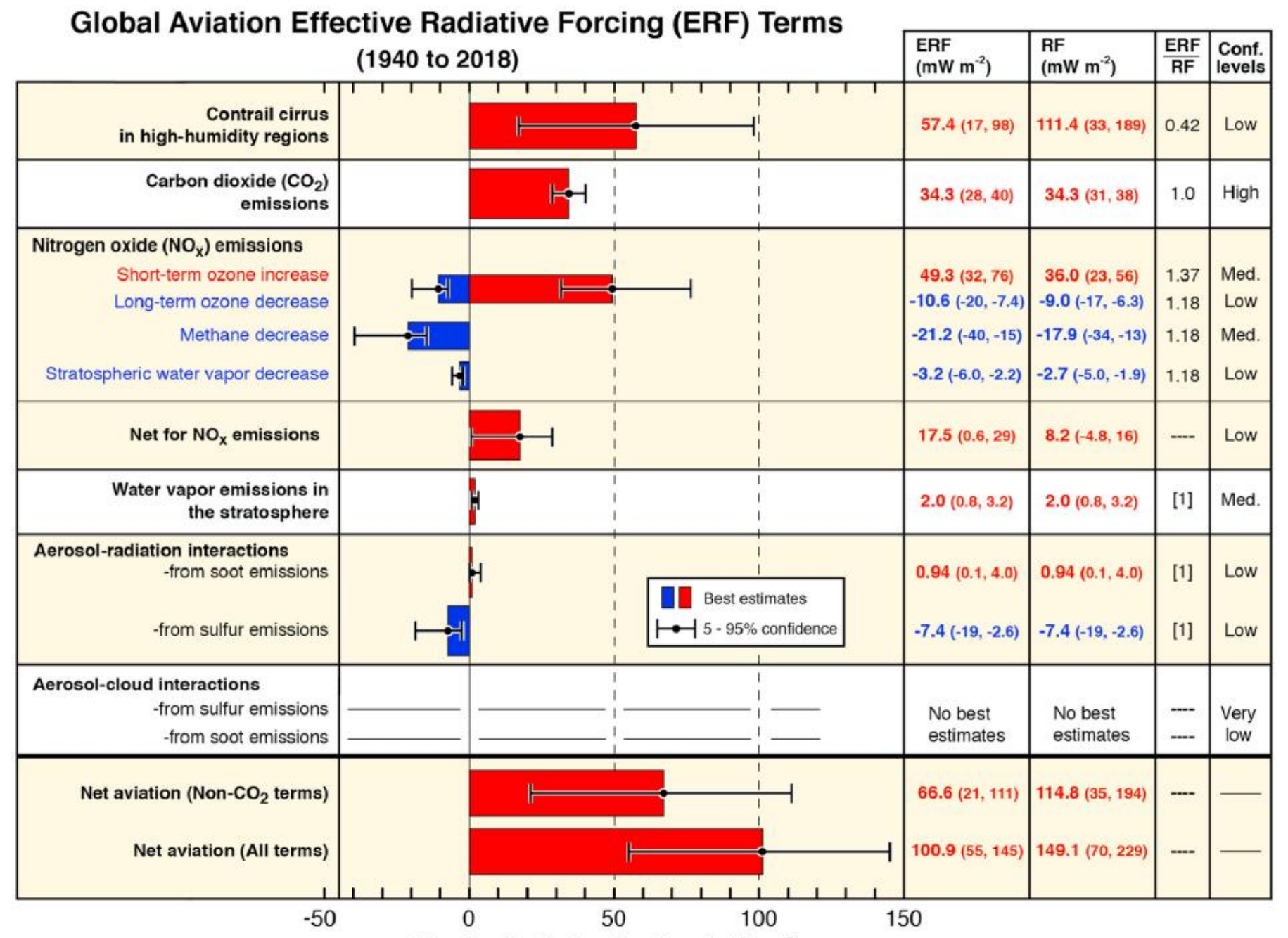
Aviation climate impact

Air traffic affects the global climate mainly through contrails, CO_2 and NO_X emissions. Contrail cirrus is regarded to be the largest contributor to aviation induced climate impact, on the basis of radiative forcings (Lee et al., 2021). Contrail cirrus develops from line-shaped contrails which spread over large areas when the ambient air is cold and humid enough.

Here we present results from global climate model simulations with fixed sea surface temperature (FSST) to derive various types of radiative forcings for contrail cirrus and simulations with interactive ocean to derive the corresponding surface temperature change. The simulations were further evaluated by feedback analysis in order to identify the individual processes that characterize the response behavior in the contrail cirrus case.



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

	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions -from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions -from sulfur emissions -from soot emissions	No best estimates	No best estimates	---- ----	Very low
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

Lee et al. (2021)

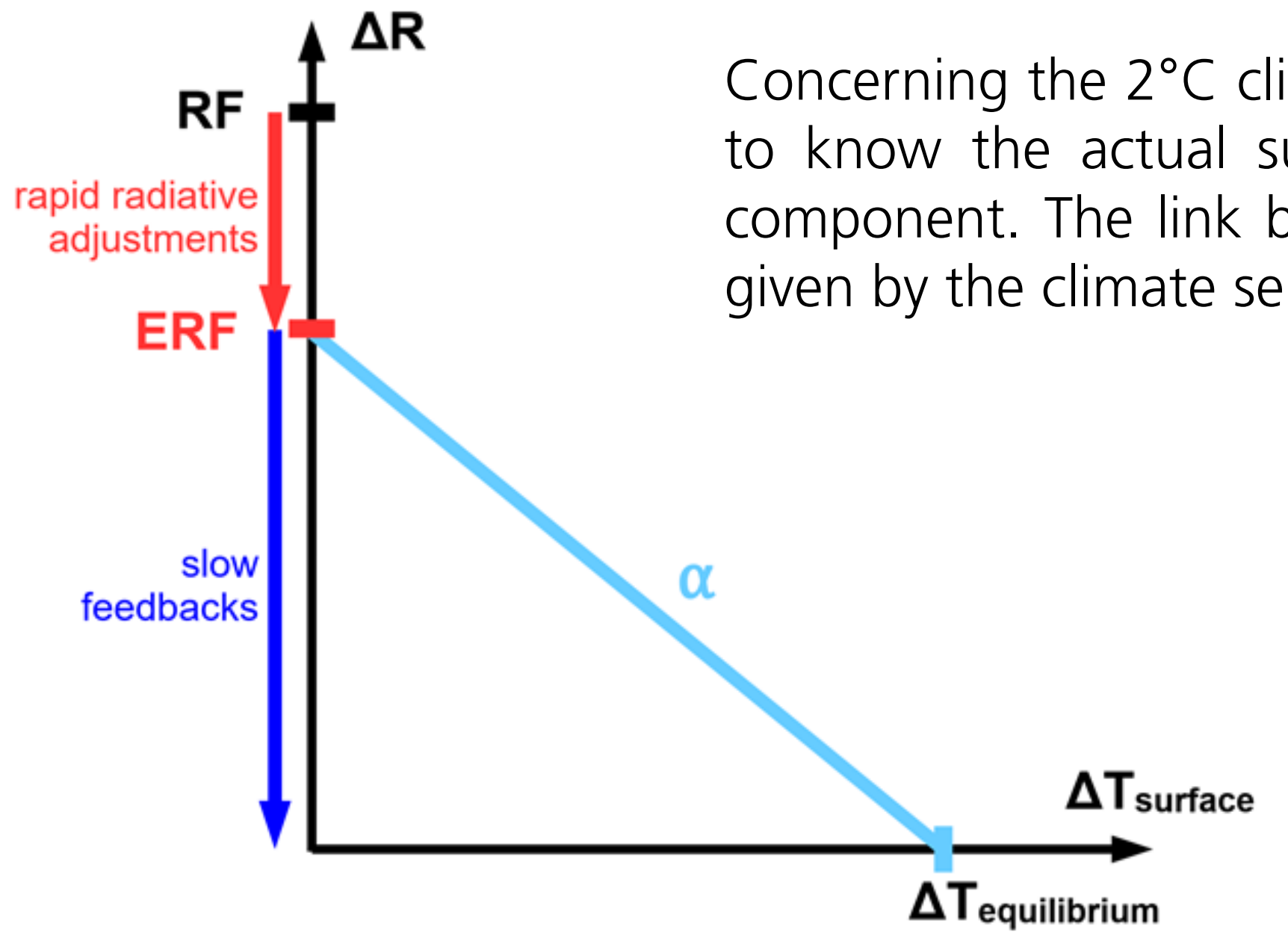
Climate model

The state-of-the-art contrail cirrus parametrization (CCMod) developed by Bock and Burkhardt (2016) was implemented in the ECHAM/MESSy Atmospheric Chemistry (EMAC) model. As a main feature CCMod includes a microphysical two-moment scheme which means that ice water content (IWC) and ice crystal number concentration (ICNC) are both interactively simulated. Contrail cirrus is fully embedded in the hydrological cycle and thus is able to compete with natural cirrus for ambient water vapor. CCMod uses air traffic density and water vapor emissions as input. Here we utilize the AEDT air traffic inventory for the year 2050 (Wilkerson et al. 2010). Air traffic was scaled by a factor of 12 in order to identify significant signals in key parameters.

Assessing various climate impact contributions

For a long time the components contributing to global climate impact were primarily assessed on the basis of classical radiative forcings (**RF**). However, during the last 15 years the framework was revised and since the 5th IPCC assessment report the Effective Radiative Forcing (**ERF**) has become the recommended metric to use. The ERF includes rapid radiative adjustments (RA) which account for relatively fast acting feedbacks of the atmosphere as a reaction to the initial perturbation. It has been demonstrated that ERF represents a far better metric to assess the surface temperature change.

$$\mathrm{ERF} = \mathrm{RF} + \mathrm{RA}$$



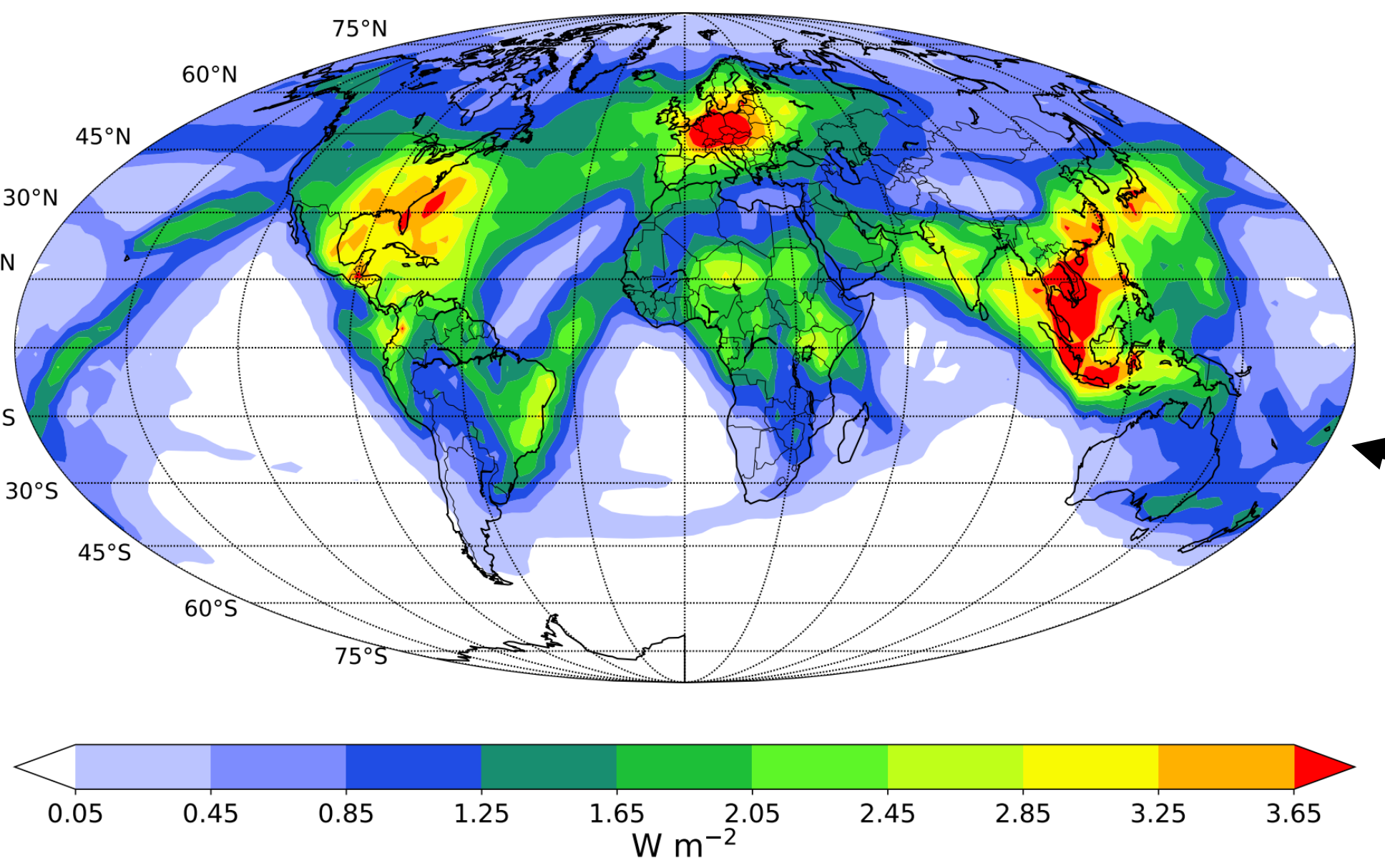
Concerning the 2°C climate target of the Paris agreement it is essential to know the actual surface temperature change induced by any RF component. The link between surface temperature change and ERF is given by the climate sensitivity (**λ**):

$$\lambda = \frac{\Delta T_{\mathrm{surface}}}{\mathrm{ERF}} = -\frac{1}{\alpha}$$

As the climate sensitivity parameter may be perturbation-dependent, hence it is sensible to introduce an efficacy parameter (**r**) to describe the potential of a non-CO_2 ERF to affect global warming:

$$\Delta T_{\mathrm{surface}} = \lambda_{CO_2} \cdot r \cdot \mathrm{ERF}$$

Radiative forcings



Simulations with Fixed Sea Surface Temperature (FSST) were performed to determine the radiative impact of contrail cirrus. For a 12 times scaling of air traffic the following radiative forcings were derived:

RF: 858 mW$\,$m^{-2}

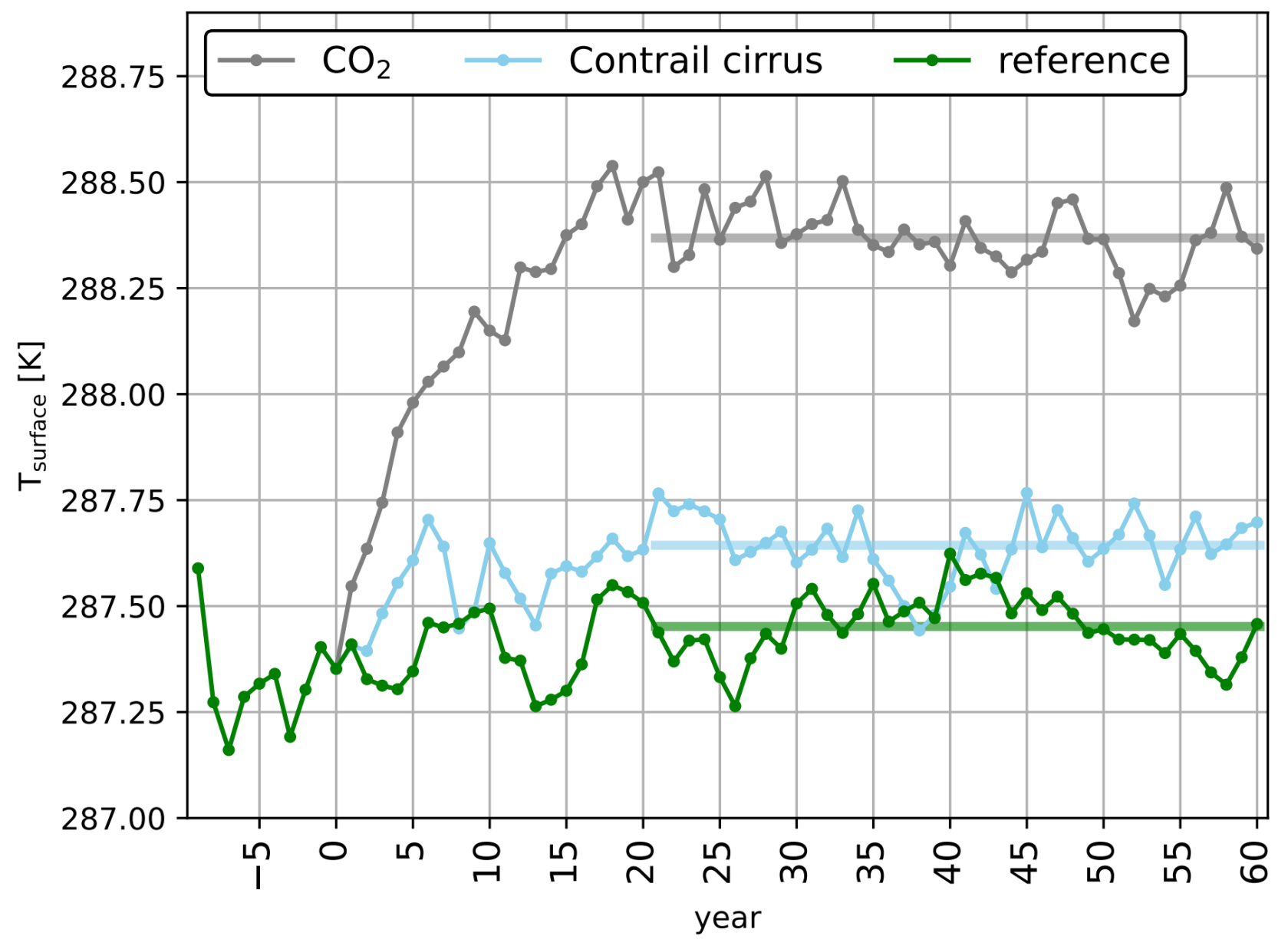
ERF: 568 mW$\,$m^{-2}

Thus, the ERF is reduced to about 65% compared to the classical RF.

As ERF is assumed to be a better predictor for the expected global surface temperature response, this ERF reduction suggests that contrail cirrus has a reduced effect on global warming, which can be verified in coupled atmosphere-ocean simulations.

Surface temperature change and climate sensitivity

Simulations with a coupled mixed layer ocean were run to determine the actual climate response. The CO_2 increase was normalized to match the RF of contrail cirrus in magnitude for a fair comparison. The resulting mean surface temperature response is almost 5 times larger for CO_2 than for contrail cirrus, i.e., the climate sensitivity is substantially lower in the latter case. This indicates a surprisingly low (**0.4**) efficacy of contrail cirrus ERF to affect the climate in terms of surface temperature change.



Outlook: Nudging simulations

The contrail cirrus simulations presented here are based on a 12 times scaling of the underlying air traffic inventory in order to ensure statistically significant results. To reduce statistical noise we plan to apply the nudging approach which might allow us to perform unscaled and thus more realistic simulations.

However, Forster et al. (2016) have expressed a warning that the full evolution of feedbacks may be suppressed in the case of nudged simulations. Anyway, since the feedbacks have already been determined without nudging, the setup used here provides an ideal basis for comparison.

Take home messages

- **Contrail cirrus Effective Radiative Forcing (ERF) is significantly lower than the corresponding classical Radiative Forcing (RF): ERF < RF**
- **Contrail cirrus efficiency to warm the Earth's surface turns out to be much weaker compared to CO_2: r ≈ 0.4 << 1**
- **The actual climate impact on surface temperature may be larger for CO_2 than for contrail cirrus: $\Delta T^{(eq)}_{\text{Contrail Cirrus}} < \Delta T^{(eq)}_{CO_2}$**

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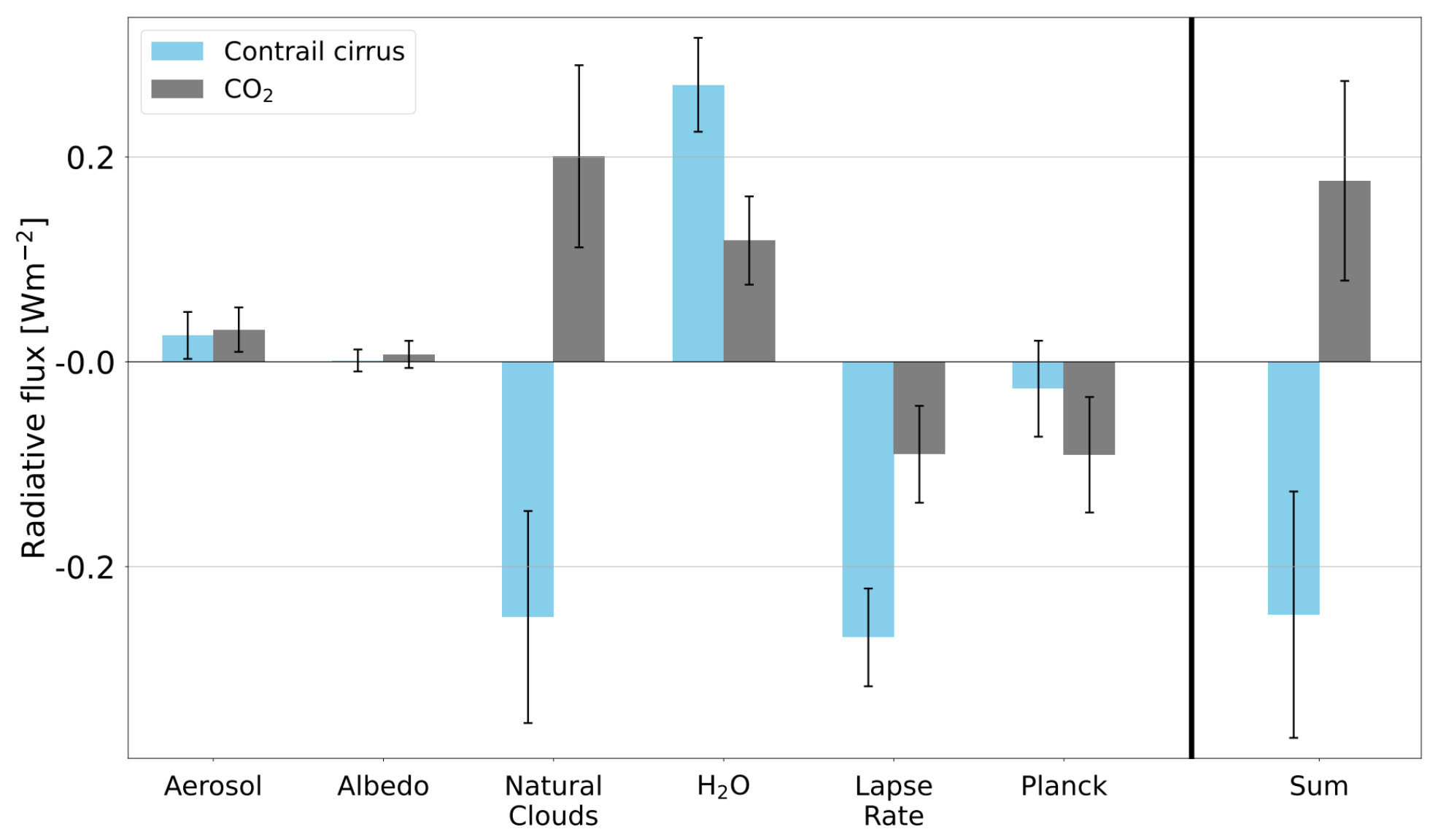
Rapid radiative adjustments



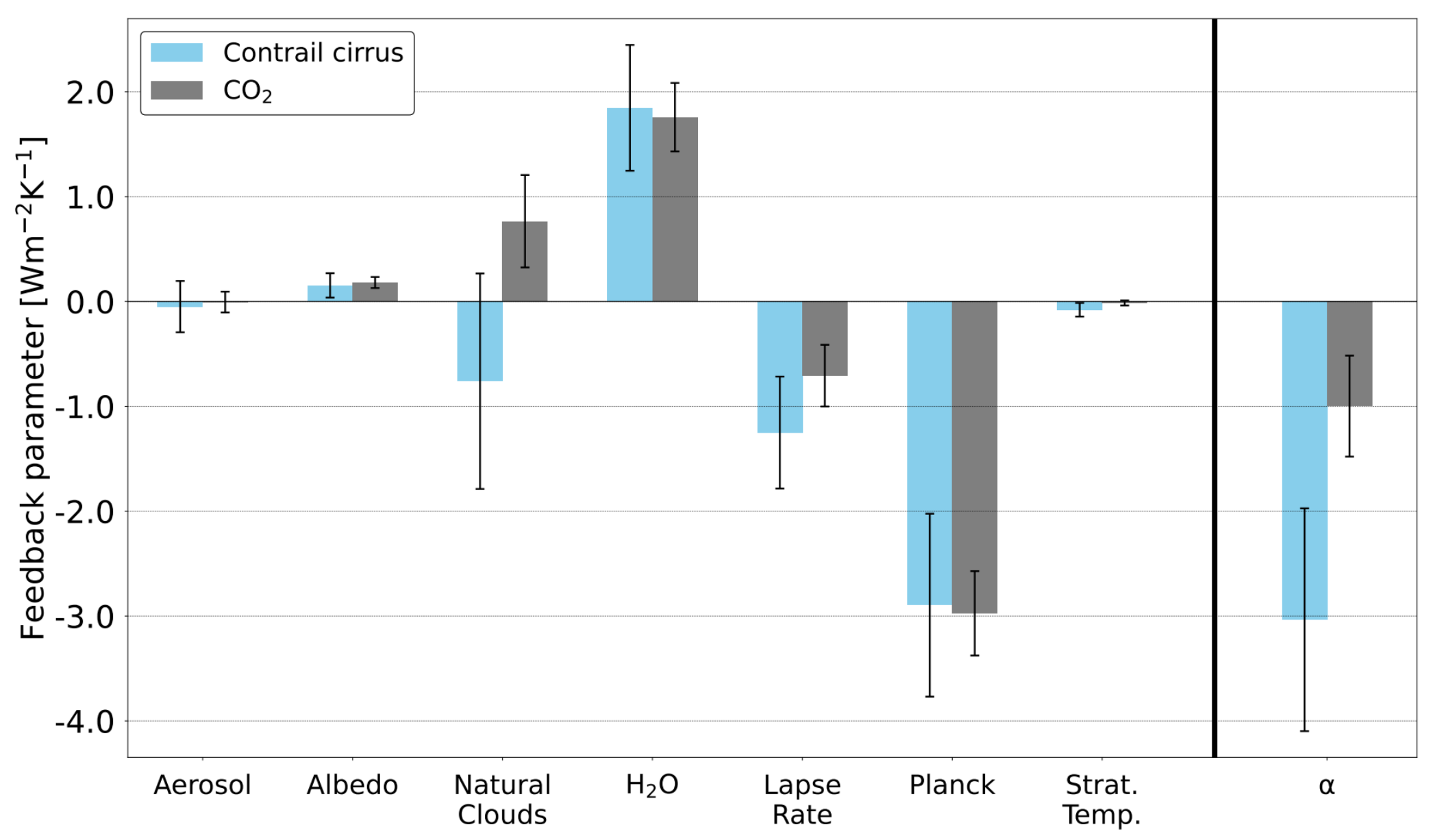
The partial radiative perturbation (PRP) method (e.g., Rieger et al., 2017) has been applied to determine the rapid radiative adjustments of contrail cirrus. Rapid radiative adjustments reveal the physical origin of the large reduction of contrail cirrus ERF compared to RF.

A strong negative natural cloud adjustment is found to be the main driver of the ERF reduction, and can be explained by contrail cirrus growing at the expense of natural cirrus by consuming ambient humidity. Unlike the CO_2 reference case, for contrail cirrus the positive water vapor adjustment is almost completely compensated by the negative lapse rate adjustment. Both are connected to a temperature increase in the upper troposphere directly below contrail cirrus.

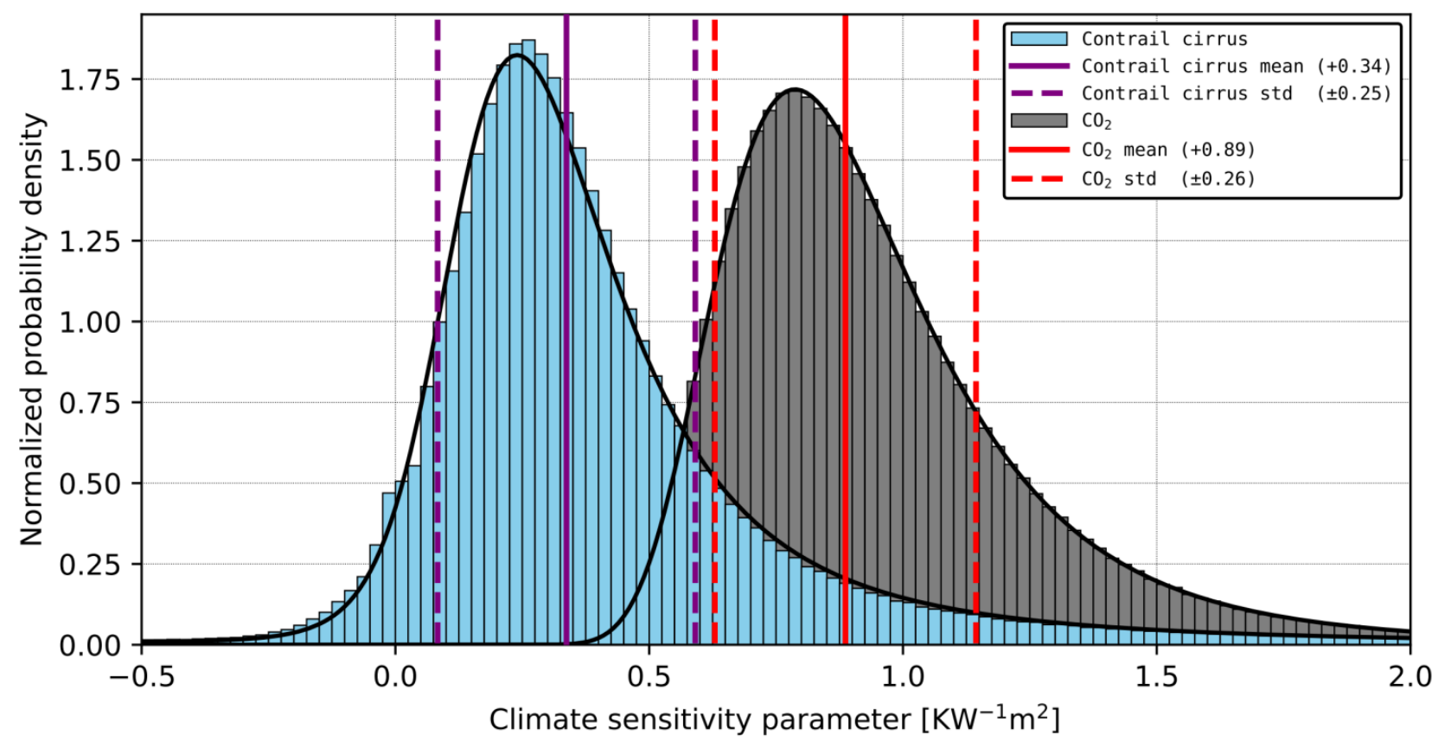
Slow feedbacks

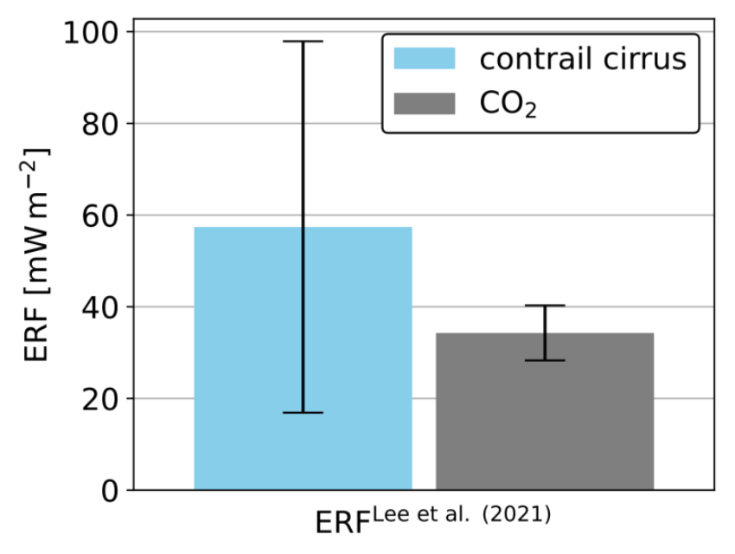
The feedback parameters shown here (slow feedbacks divided by surface temperature change) explain the different capabilities of contrail cirrus and CO_2 to warm Earth's surface. Besides the lapse-rate feedback parameter, the natural cloud feedback parameter constitutes the largest difference.

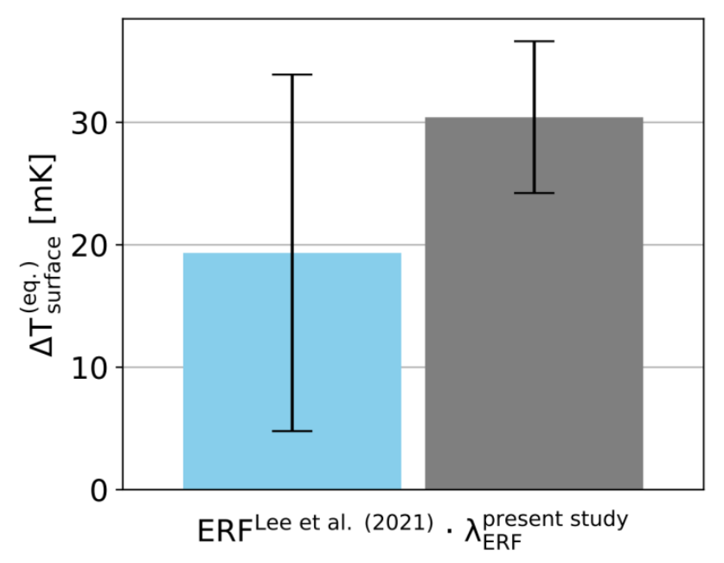
Its origin can be found in low- and mid-level clouds decreasing in case of CO_2, a feature largely absent from the contrail cirrus simulation.



Equilibrium surface temperature change from 2018 forcings







In order to derive an estimation for the actual surface temperature changes induced by contrail cirrus and aviation CO_2 emissions the ERFs provided by the Lee et al. (2021) assessment report for the year 2018 were used (see bottom left box). On the basis of ERFs the supposed climate impact of contrail cirrus is larger than for CO_2.

When multiplying these ERFs with the climate sensitivities (λ) derived here (see upper plot), the equilibrium surface temperature changes for both forcers can be estimated (see bottom right box). This results in a reversed ranking of the best estimates for contrail cirrus and aviation CO_2, a matter of particular relevance for contrail mitigation at the expense of more fuel use.

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