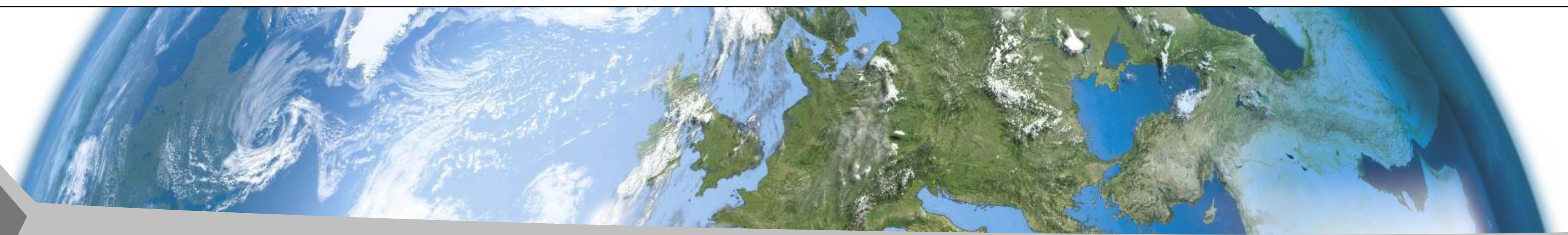


A23G-2905

# Radiative Forcing and Rapid Atmospheric Adjustments Induced by Contrail Cirrus

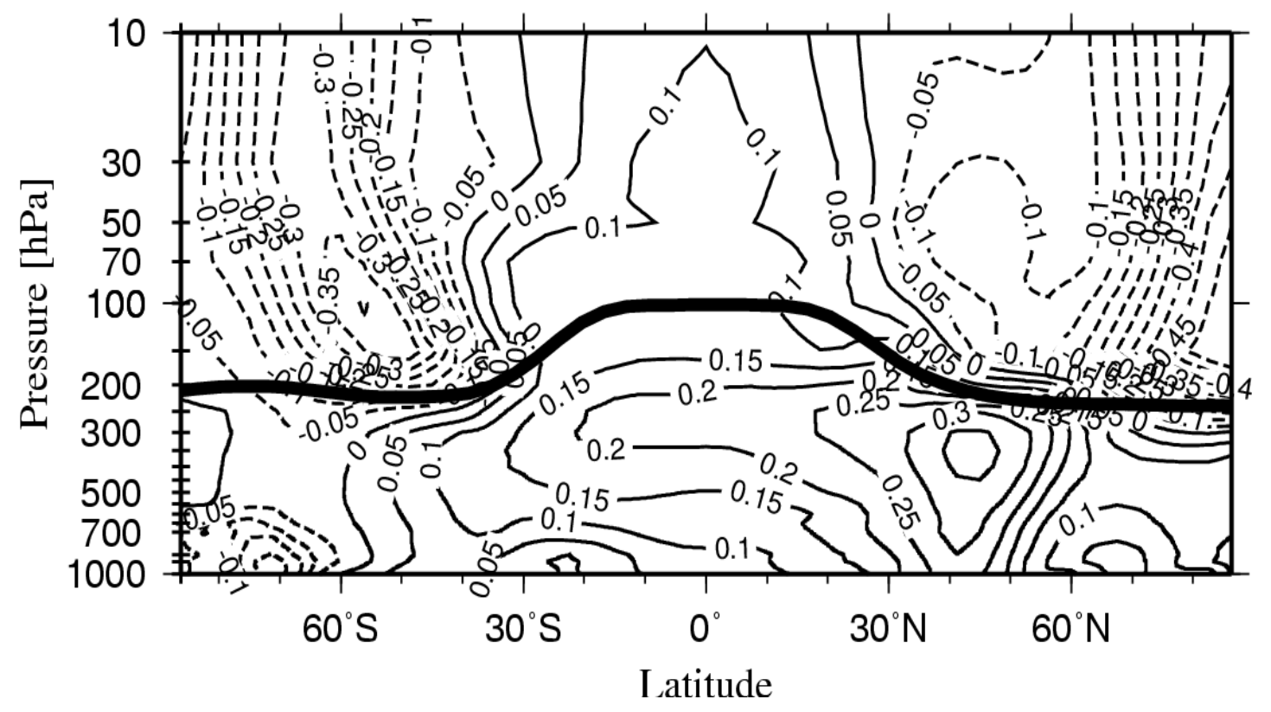
Marius Bickel, Michael Ponater, Lisa Bock, Ulrike Burkhardt and Svenja Reineke

## Radiative Forcing, Efficacy and Climate Response

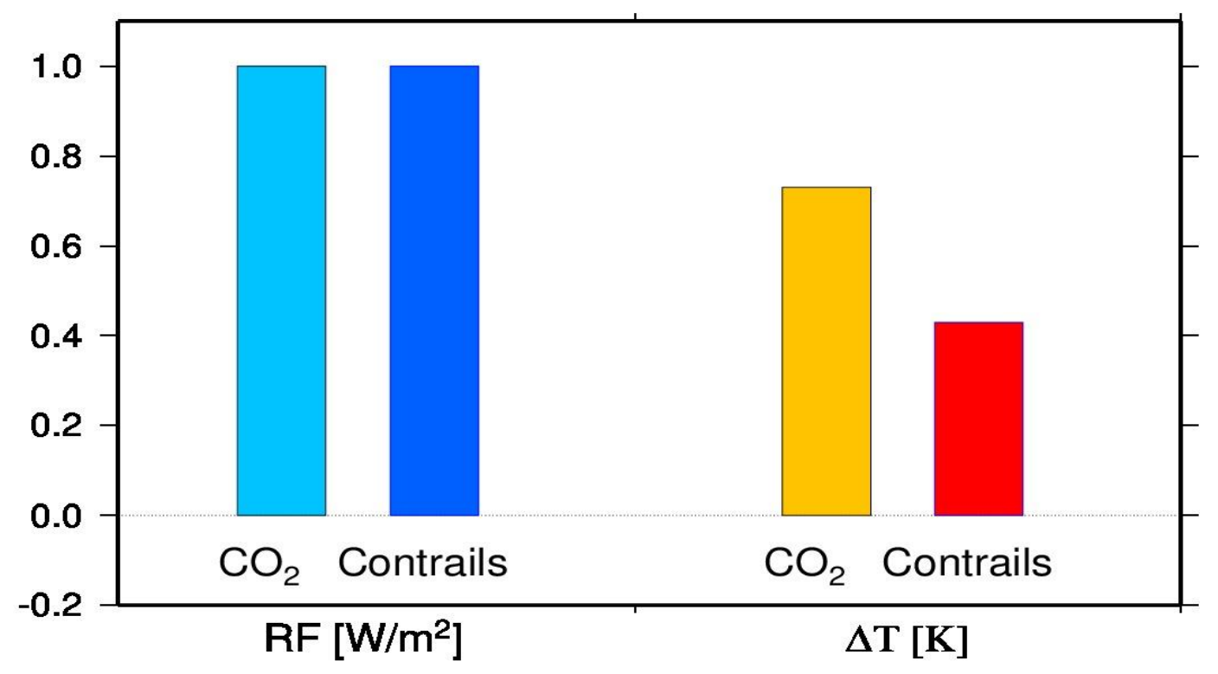
Radiative forcing ($RF$) is linked to global mean surface temperature change $\Delta T_S$ via the climate sensitivity parameter $\lambda$.
Non-$CO_2$ radiative forcings such as contrails are said to have reduced or enhanced efficacy $r$, if the surface temperature response per unit radiative forcing (i.e, $\lambda$) is smaller or larger than the reference climate sensitivity parameter $\lambda_{CO_2}$ (Hansen et al., 2005):

$$\Delta T_S = \lambda \cdot RF = r \cdot \lambda_{CO_2} \cdot RF$$

Several studies indicate that line-shaped contrails have substantially reduced efficacy (Ponater et al., 2005; Rap et al, 2010). It is unknown whether this holds for contrail cirrus as well. The feedbacks controlling deviations from $CO_2$-induced $RF$ are not sufficiently clarified so far.

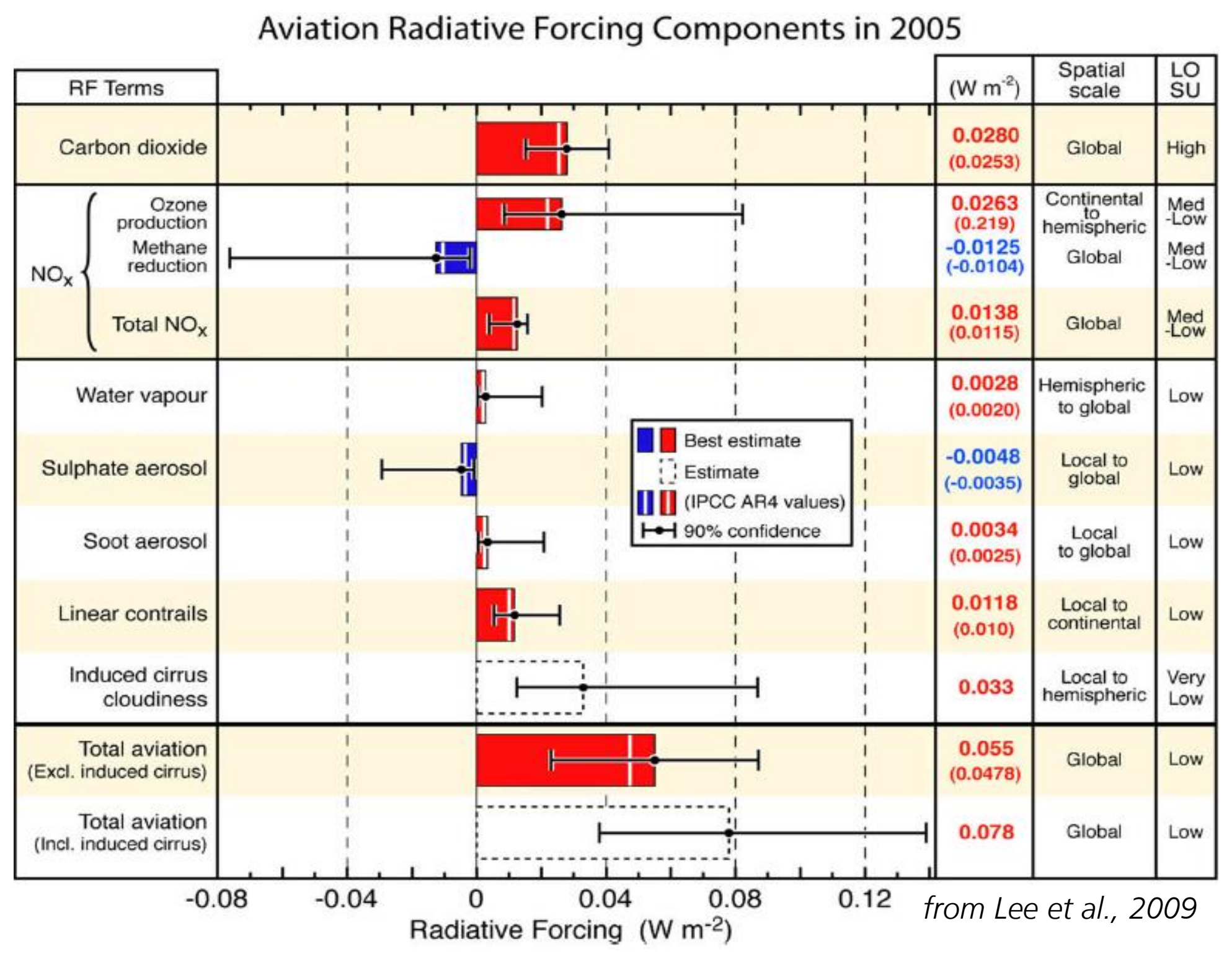


*Simulated zonal mean temperature response to scaled $RF$ from line-shaped contrails (Ponater et al., 2005).*

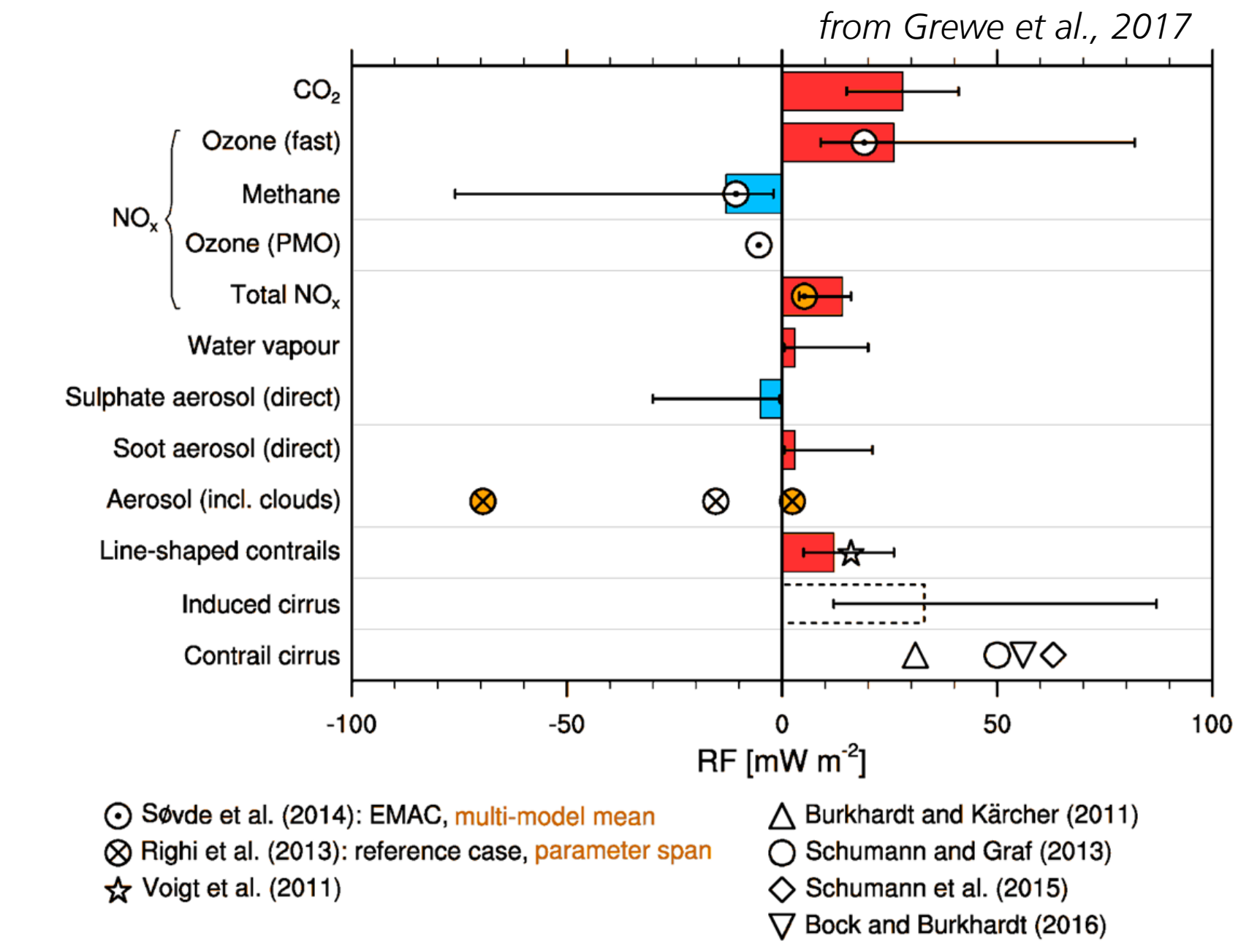


*Illustrative scheme: Efficacy of line-shaped contrails is only about 60% of a $CO_2$ forcing of equivalent strength (Assumed climate sensitivity parameter: 0.70 K/(Wm²). )*

## Contrails and Contrail Cirrus as Part of Aviation Global Climate Impact



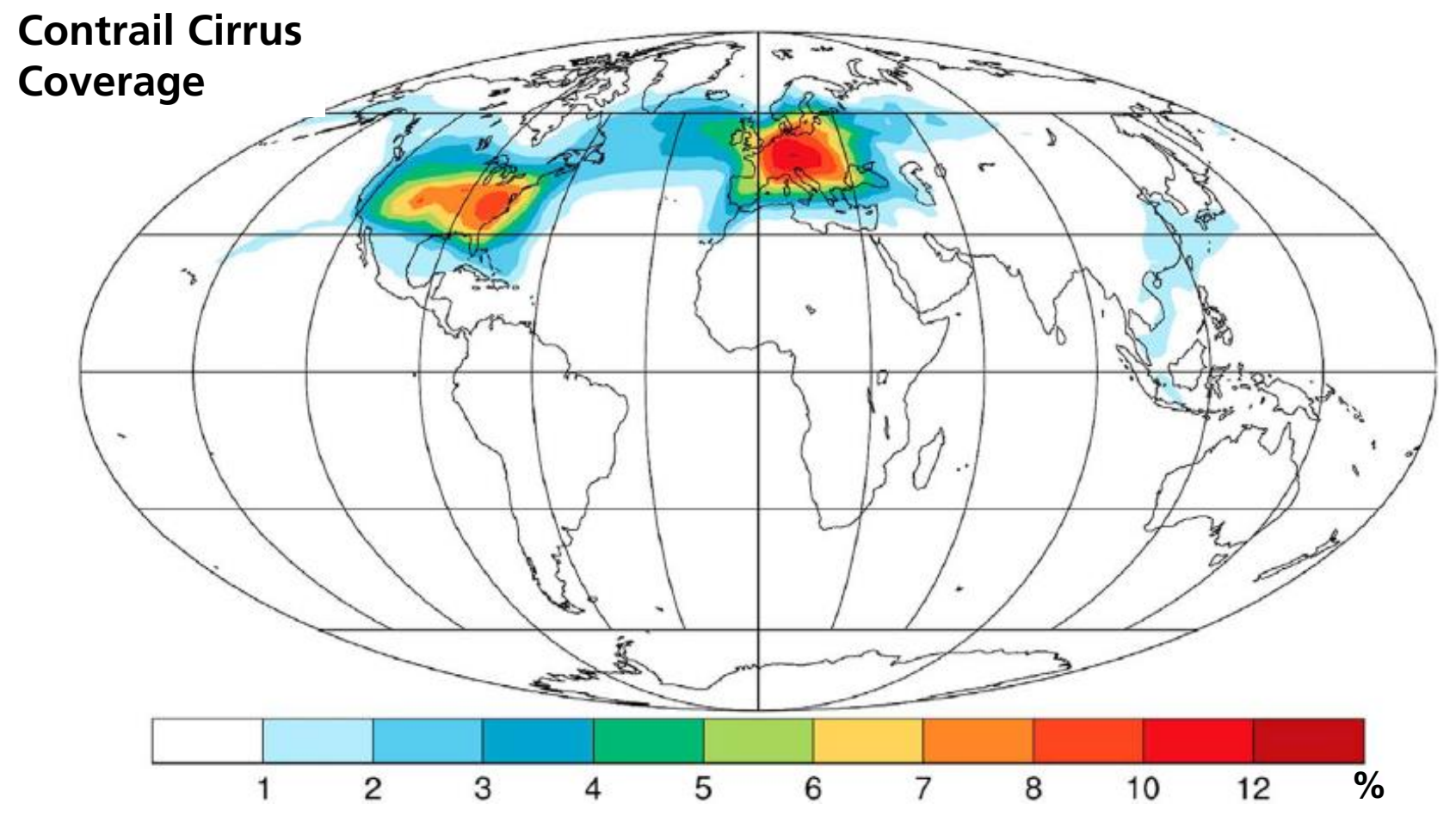
from Lee et al., 2009



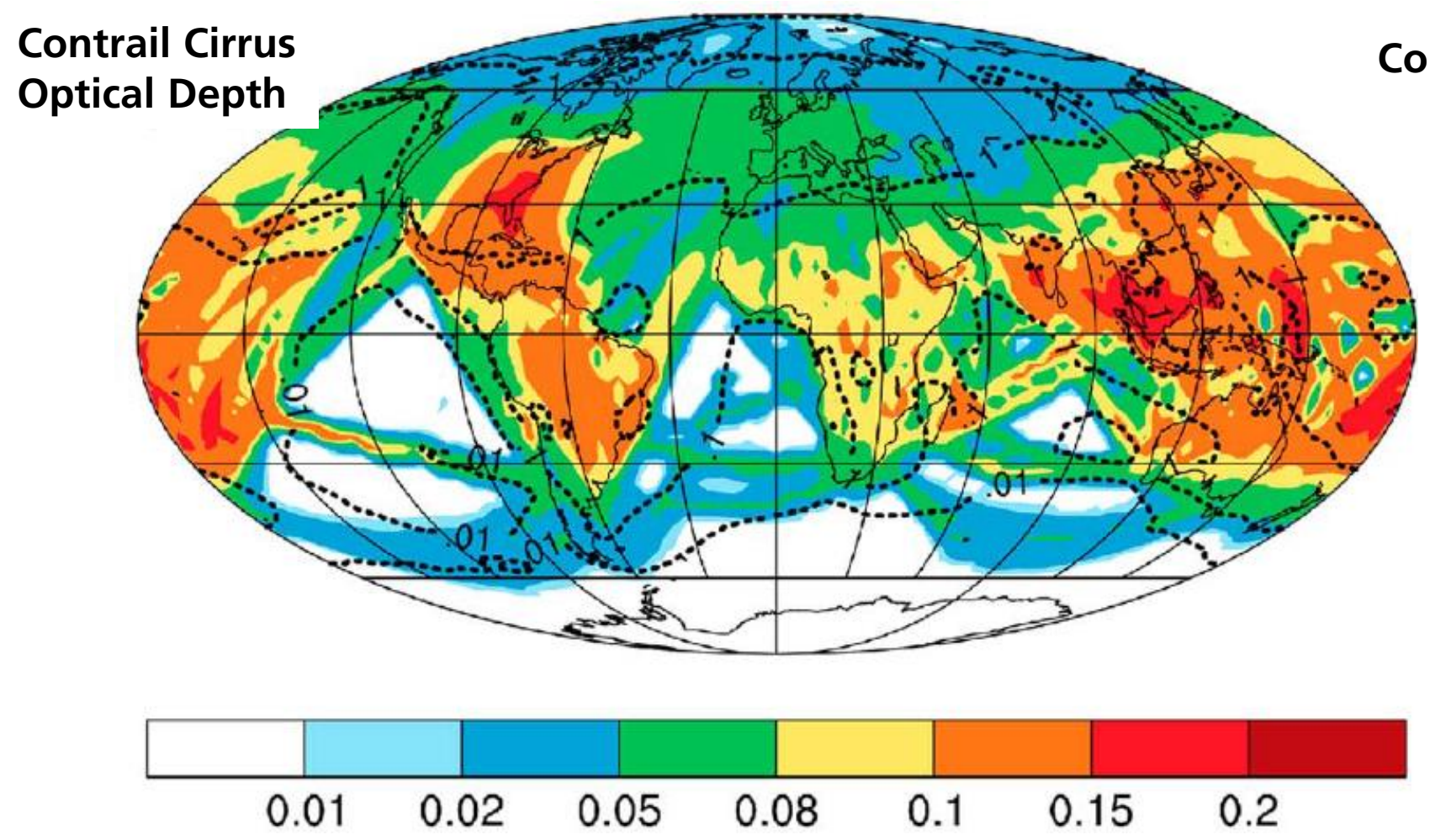
Various components to aviation climate impact have usually been assessed and compared in terms of RF, which can be determined even for small contributors. Contrail cirrus is among the largest contributors and rather difficult to quantify. The aviation climate impact assessment of Lee et al. (2009) only gave a tentative value.

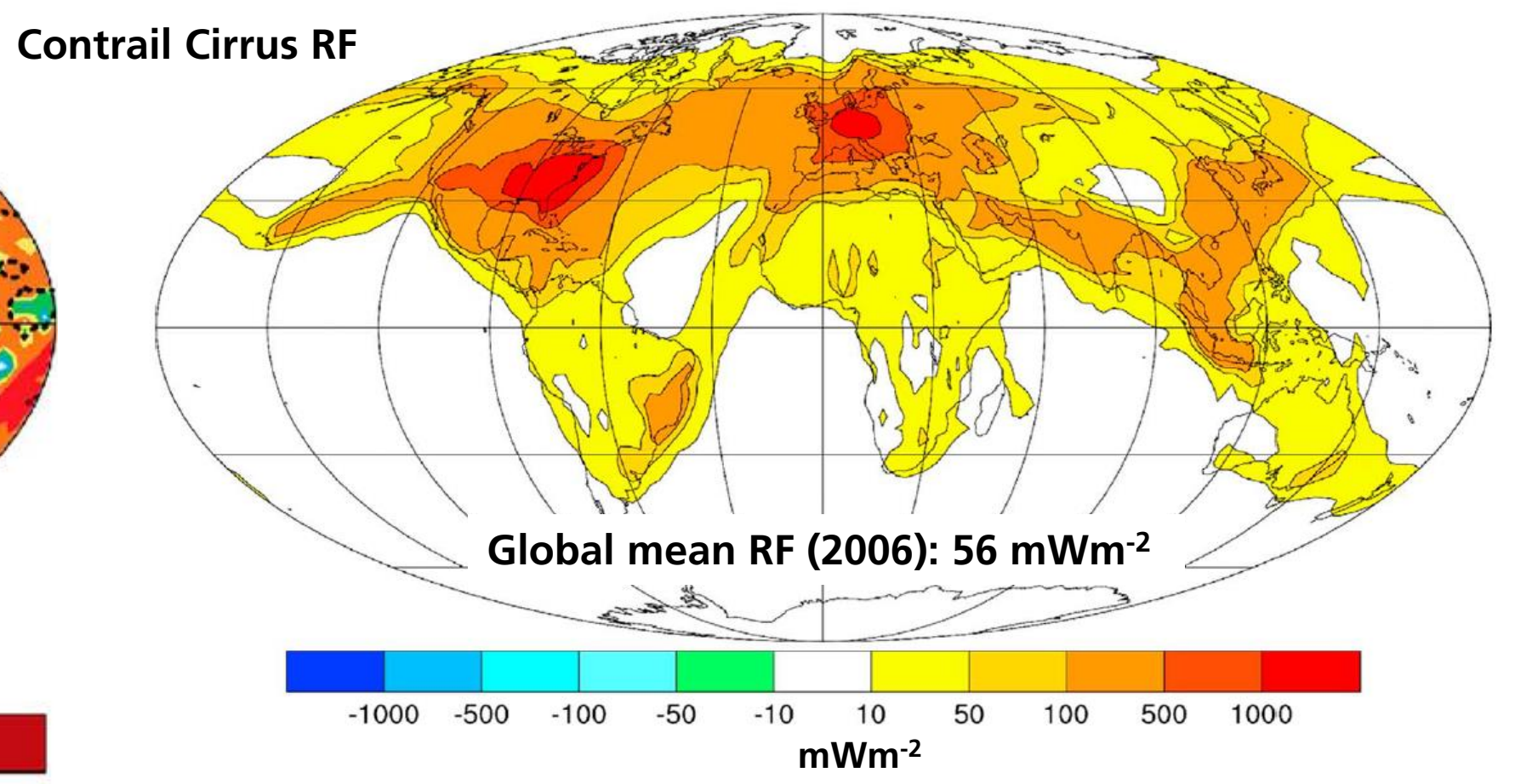
Since the Lee assessment further contrail cirrus estimates were published, confirming its importance in terms of RF (Grewe et al., 2017). No *effective radiative forcing* (ERF) estimate of contrail cirrus has been given yet, though ERF is now considered a superior metric assessing climate impact components, because efficacies ($r'$) under the ERF framework ($\Delta T_S = r' \cdot \lambda'_{CO_2} \cdot ERF$) have been found to deviate less from unity ($CO_2$) (Ramaswamy et al., 2019).

## Contrail Cirrus in a Global Climate Model



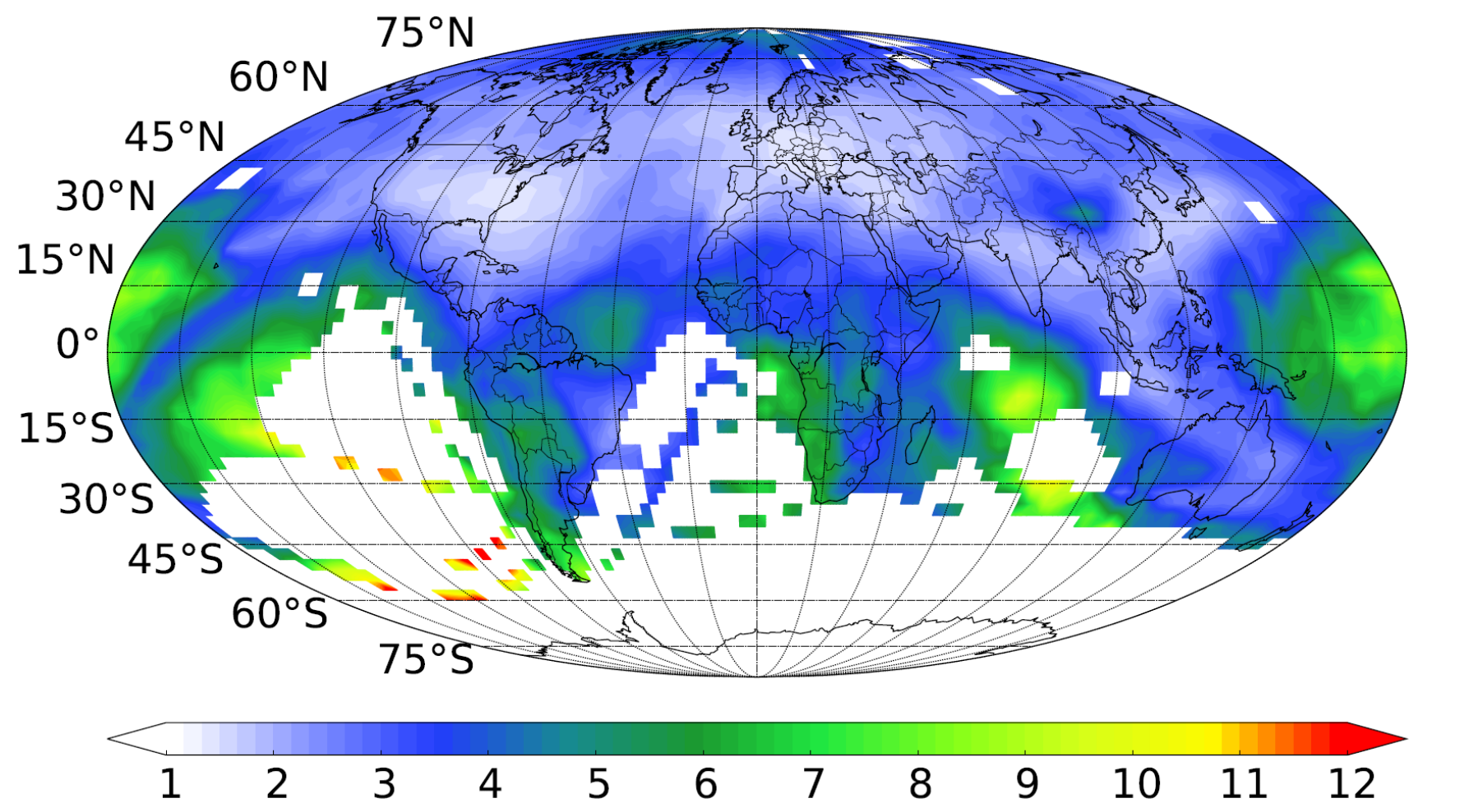
The work presented here builds on results from Bock and Burkhardt (2016a,b), who have established a contrail cirrus parameterization in the ECHAM5 global climate model framework. Using the AEDT flight distance inventory for 2006, they simulate a global mean contrail cirrus coverage of 1.2 % and a contrail cirrus RF of 56 mWm$^{-2}$.
The corresponding RF result for the AEDT 2050 inventory is between 159 mWm$^{-2}$ and 182 mWm$^{-2}$ (Bock and Burkhardt, 2019). This 2050 RF estimate forms the starting point for the ERF determination approach focused on here.





from Bock and Burkhardt, 2016b

## Determining Contrail Cirrus Effective Radiative Forcing

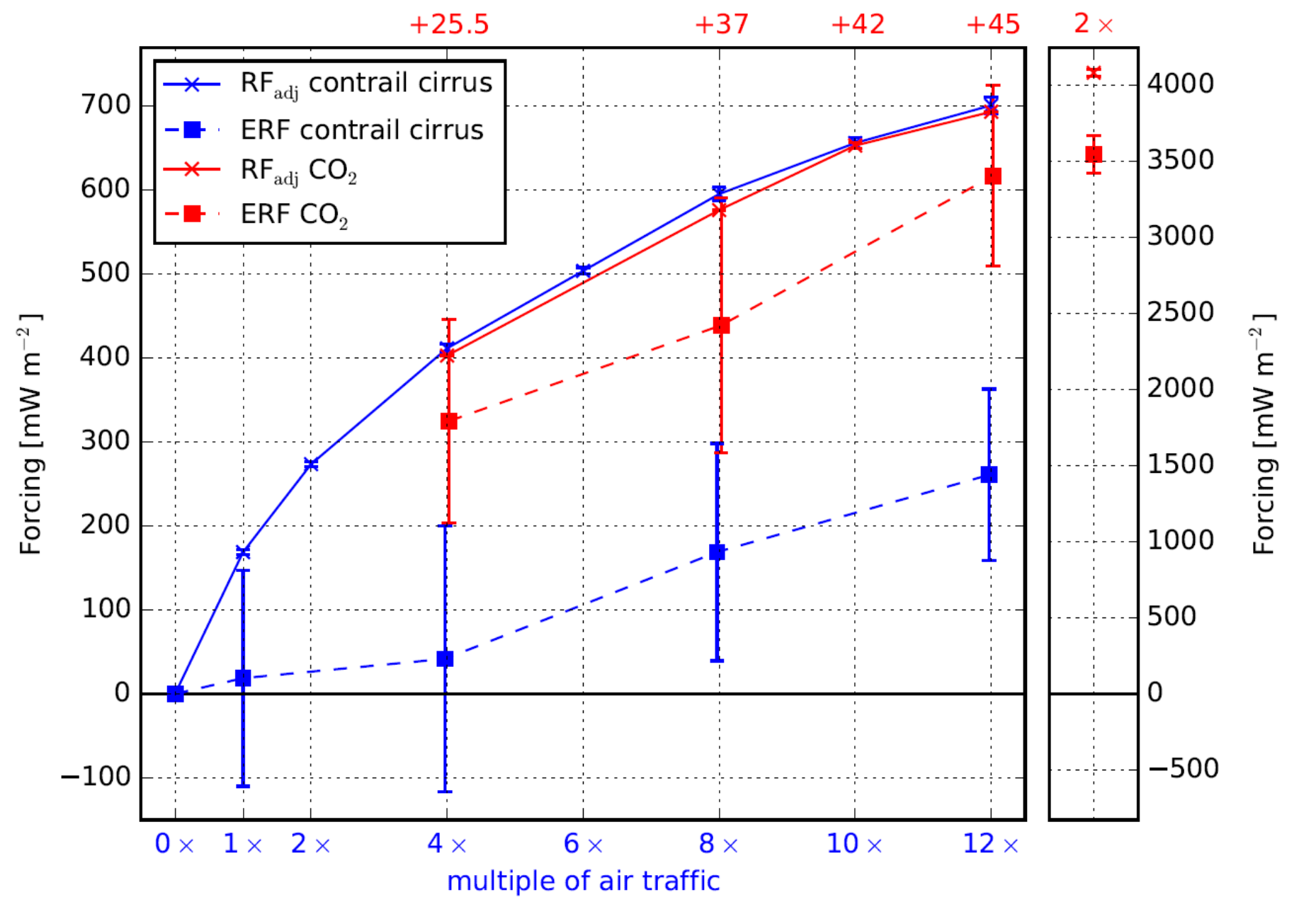


*Ratio of contrail cirrus cover yielded in the simulation with 12-fold air traffic scaling, relative to the simulation with unscaled air traffic.*

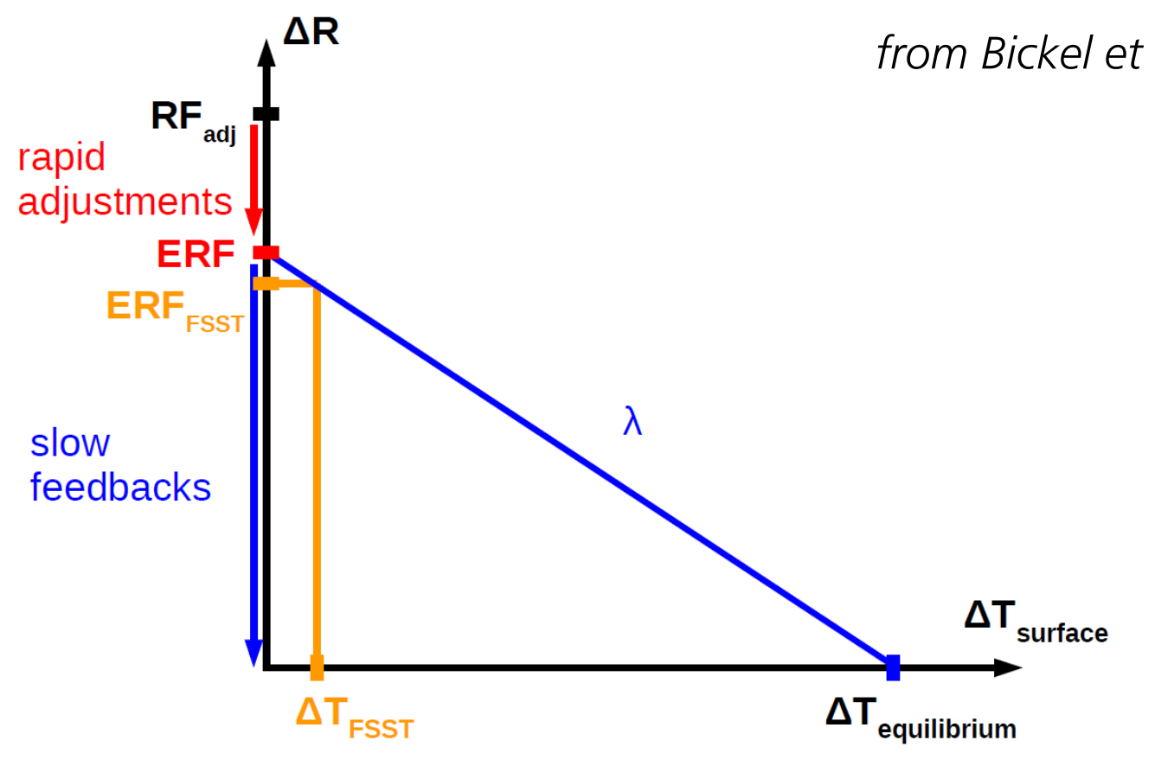
ERF is obtained from fixed SST simulations with and without contrail cirrus, a method involving much more statistical uncertainty than conventional RF, which can be yielded by radiation double calling. Determining ERF, hence, requires scaling of the basic (2050) inventory. This scaling is associated with non-linearities of different degree in different regions (see left), as a state of saturation is gradually approached, especially where 2050 air traffic is already strong.

*from Bickel et al. (2019)*

Throughout the contrail cirrus simulation series with different scaling factors, ERF is consistently more than 50% smaller than the corresponding RF (right, blue lines). ERF is also smaller than RF in the $CO_2$ increase simulations, but then the reduction is much weaker (red lines). It may be concluded that contrail cirrus ERF is only about 40% of the $CO_2$ ERF, if both effects induce the same classical RF.
The necessity of the scaling is most obvious for contrail cirrus ERF calculated from the original 2050 inventory. This simulation alone does not allow to claim a positive ERF.

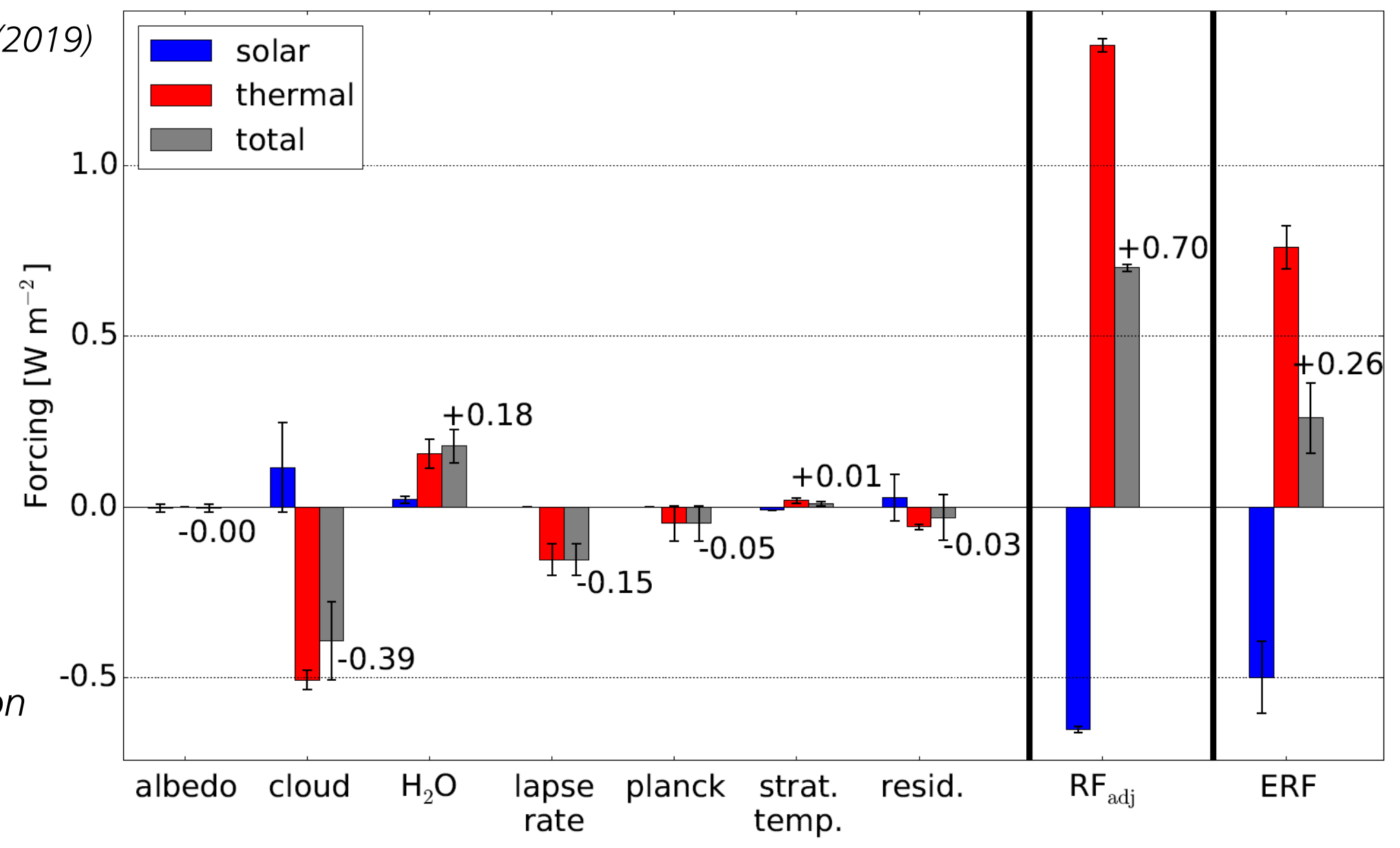


## ERF Reduction by Rapid Radiative Adjustment



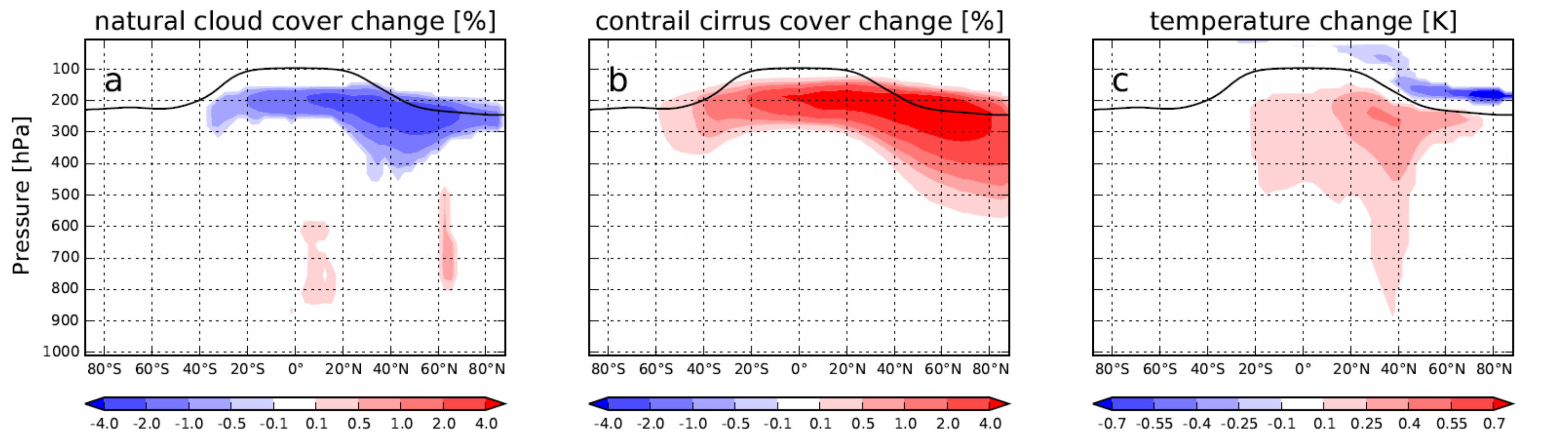
*The difference between ERF and RF originates from rapid radiative adjustments in the troposphere that modify RF on time scales faster than the surface temperature response.*

*from Bickel et al. (2019)*



In order to understand the low ERF for contrail cirrus, rapid radiative adjustments have been determined using an offline ECHAM5 radiation module for partial radiative perturbation analysis (Rieger et al., 2017). Large negative natural cloud adjustment is identified as the main driver for ERF reduction (right panel). This effect is much weaker in the $CO_2$ case (see Bickel et al., 2019). A negative lapse-rate adjustment also makes a contribution, but less, as it is widely compensated via its close coupling to the (positive) water vapor adjustment.

## Parameter Changes Basic to the Rapid Radiative Adjustments



*The increase in cirrus coverage from spreading contrails (b) induces a substantial impact on natural cloud coverage (a), especially on the natural cirrus developing adjacent to the contrails. This appears consistent as both processes compete in consuming ambient supersaturation available for ice nucleation. Hence, negative radiative adjustment from natural clouds can be explained.* from Bickel et al. (2019)

*Local radiative heating from the (contrail) cirrus increase mainly warms the upper troposphere (sea surface temperature being fixed), thus inducing a negative lapse rate adjustment.*

## Take Home Message

- Effective radiative forcing (ERF) of contrail cirrus is reduced by roughly 65% with respect to the classical radiative forcing (“stratosphere adjusted radiative forcing”, $RF_{adj}$).
- For a forcing induced by $CO_2$ increase the ERF is also reduced, but substantially less.
- The differences between ERF and $RF_{adj}$ can be explained consistently by analyzing rapid radiative adjustments to the forcing.
- Rapid adjustment of natural clouds is the dominating effect in reducing the ERF of contrail cirrus.
- Low ERF of contrail cirrus suggests low efficacy (to be confirmed from dedicated coupled atmosphere-ocean simulations, which will be the follow-up step to the present work).

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29.11.2019