Formation and Climate Impact of Contrail Cirrus

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Hamburg Aerospace Lecture Series (AeroLectures)
DGLR, RAeS, VDI, ZAL and HAW Hamburg, 2nd December 2021

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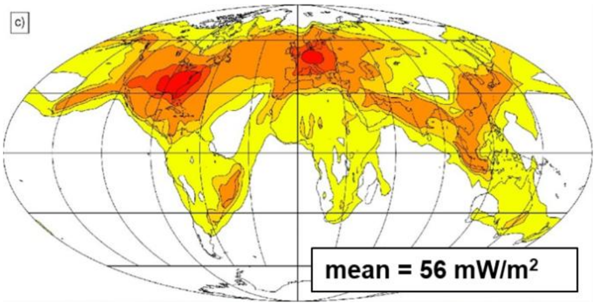
Formation and Climate Impact from Contrails



Dr. **Ulrike Burkhardt**
Institute of Atmospheric Physics,
German Aerospace Center (DLR)

Date: **Thursday, 02 December 2021, 18:00 CET**
Online: https://purl.org/ProfScholz/zoom/2021-12-02

Today, air traffic is estimated to contribute between 3.5% and 5% to the anthropogenic forcing of climate change. **Contrail cirrus**, the cirrus clouds that form within the aircraft plume, account for the **largest share of the aviation related forcing**, larger than the forcing from aviation CO2 emissions. Contrails form when the aircraft exhaust mixes with environmental air, and during this mixing the plume relative humidity increases so much that water saturation is exceeded. Contrail formation increases cirrus cloudiness and modifies the radiation budget of the earth. This change in the radiation budget can be estimated using **climate models** that include a representation of contrail cirrus processes. The impact of contrail cirrus on radiation is dependent on contrail cirrus **optical properties** and their **life time** or **coverage**. Properties and life times are controlled by microphysical processes such as ice formation, i.e. processes on the scale of a single ice crystal. Simulations can be compared to in-situ or remote sensing measurements and the sensitivity of simulated contrail cirrus properties and radiative forcing to emissions can be explored.

*After receiving her doctorate in Physics in 1997 from the Ludwig-Maximilians-University in Munich, **Ulrike Burkhardt** moved first to the University of Reading (UK) and in 2003 to the Institute of Atmospheric Physics of the German Aerospace Centre (DLR) in Oberpfaffenhofen as a research fellow. Since 2006 her research has focussed on cirrus clouds, natural cirrus and contrail cirrus, and their representation within climate models or higher resolving models. She studies the climate impact of contrail cirrus and the impact of different mitigation options.*

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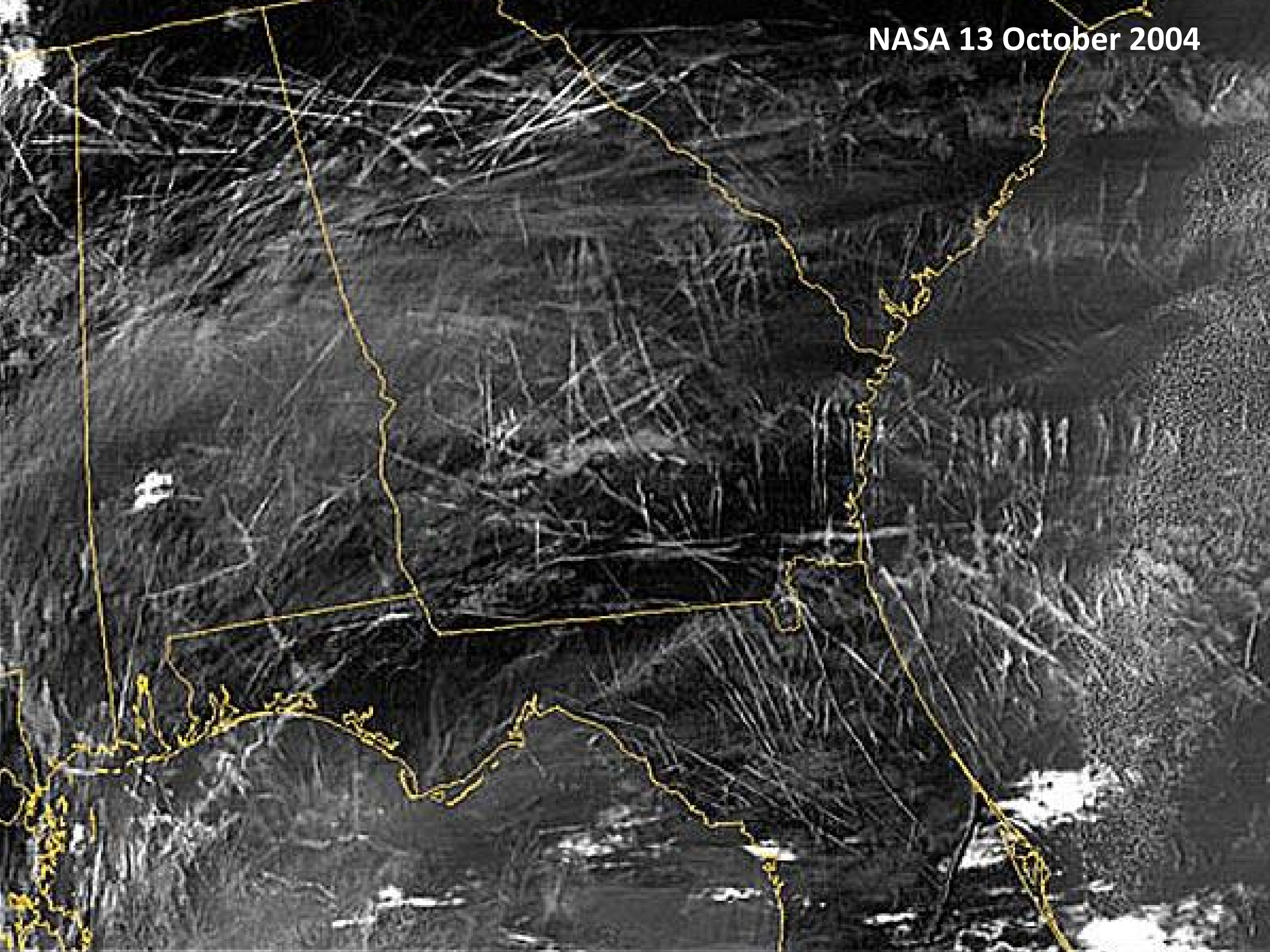
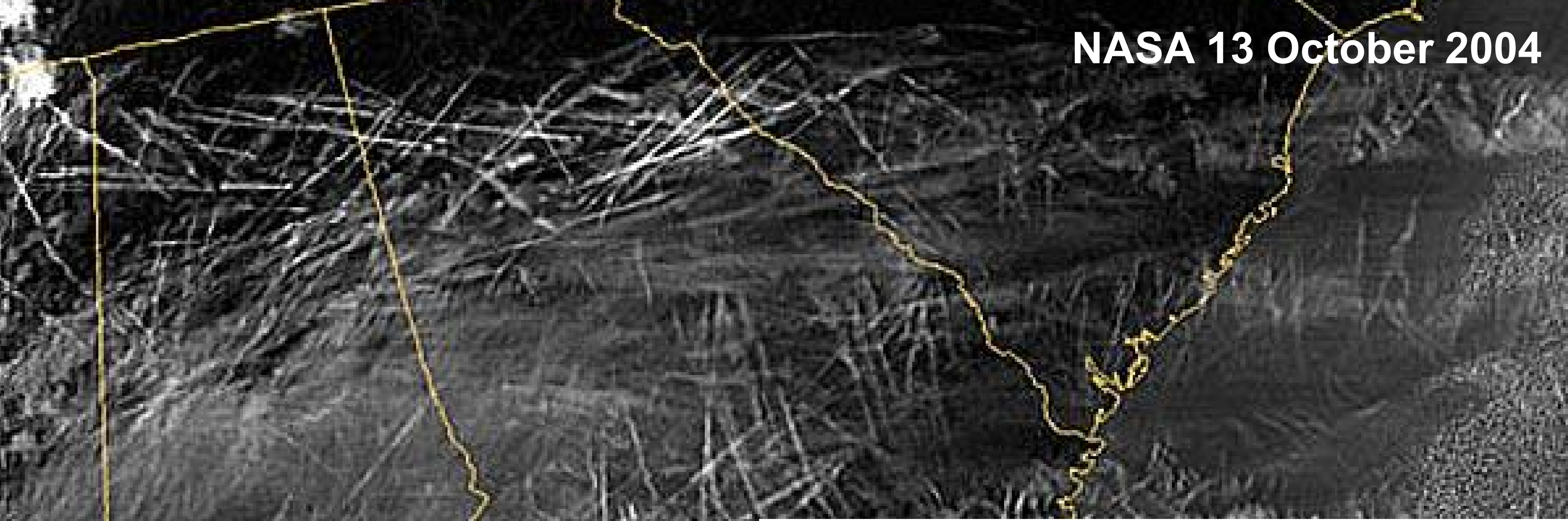


NASA 13 October 2004



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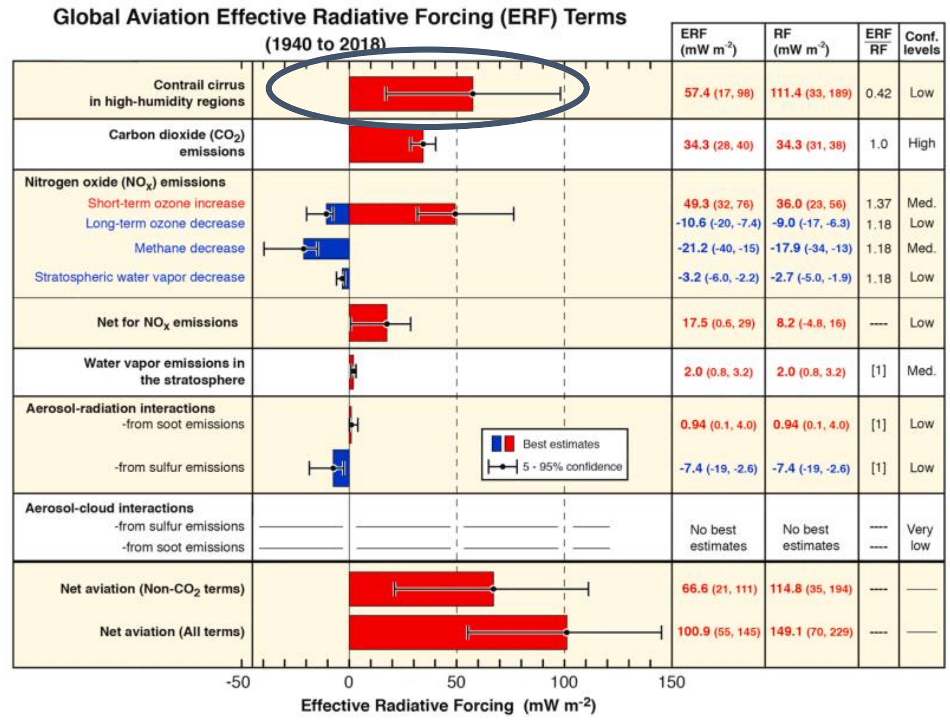
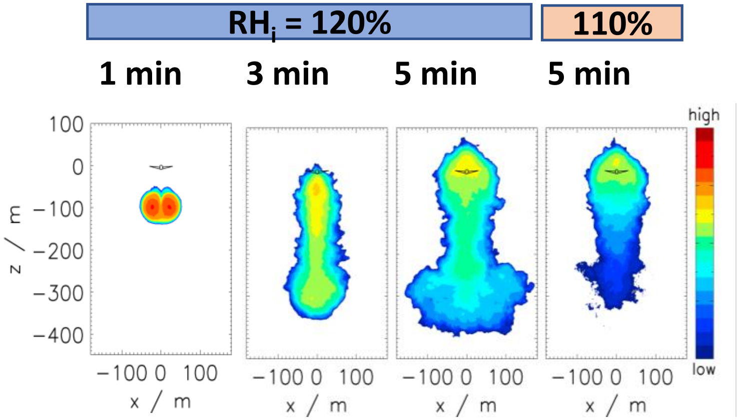


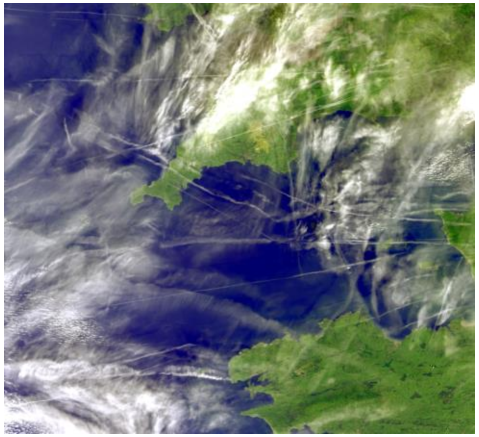
Global Aviation Effective Radiative Forcing (ERF) Terms (1940 to 2018)

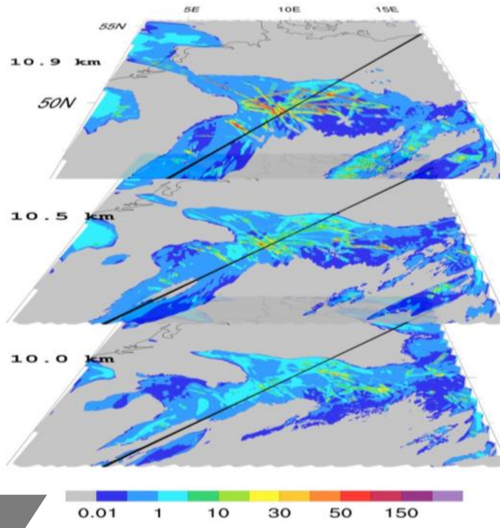
	ERF (mW m^{-2})	RF (mW m^{-2})	$\frac{ERF}{RF}$	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	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	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
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)	----	—

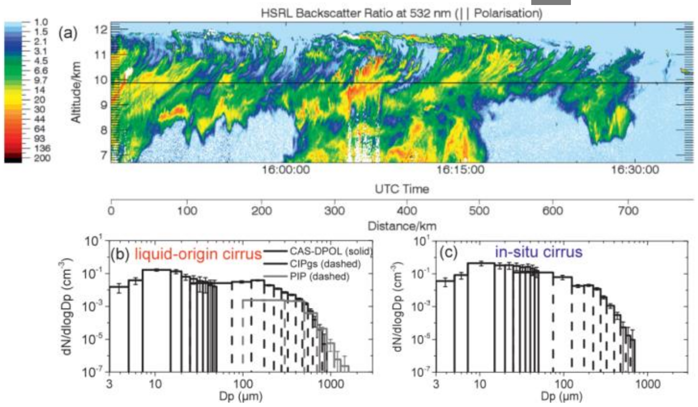
Lee et al., Atmospheric Environment, 2021

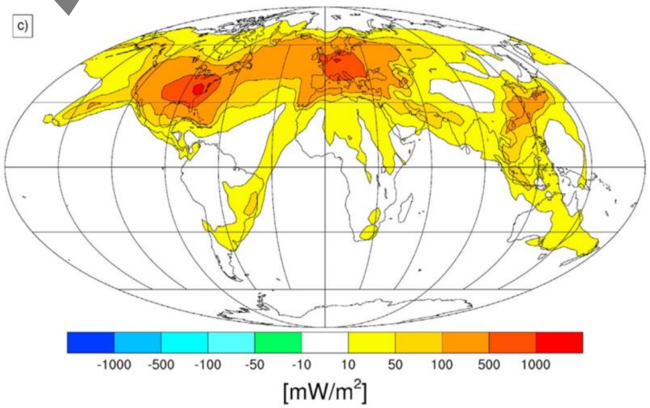
Contrail research at the DLR Institute of Atmospheric Physics



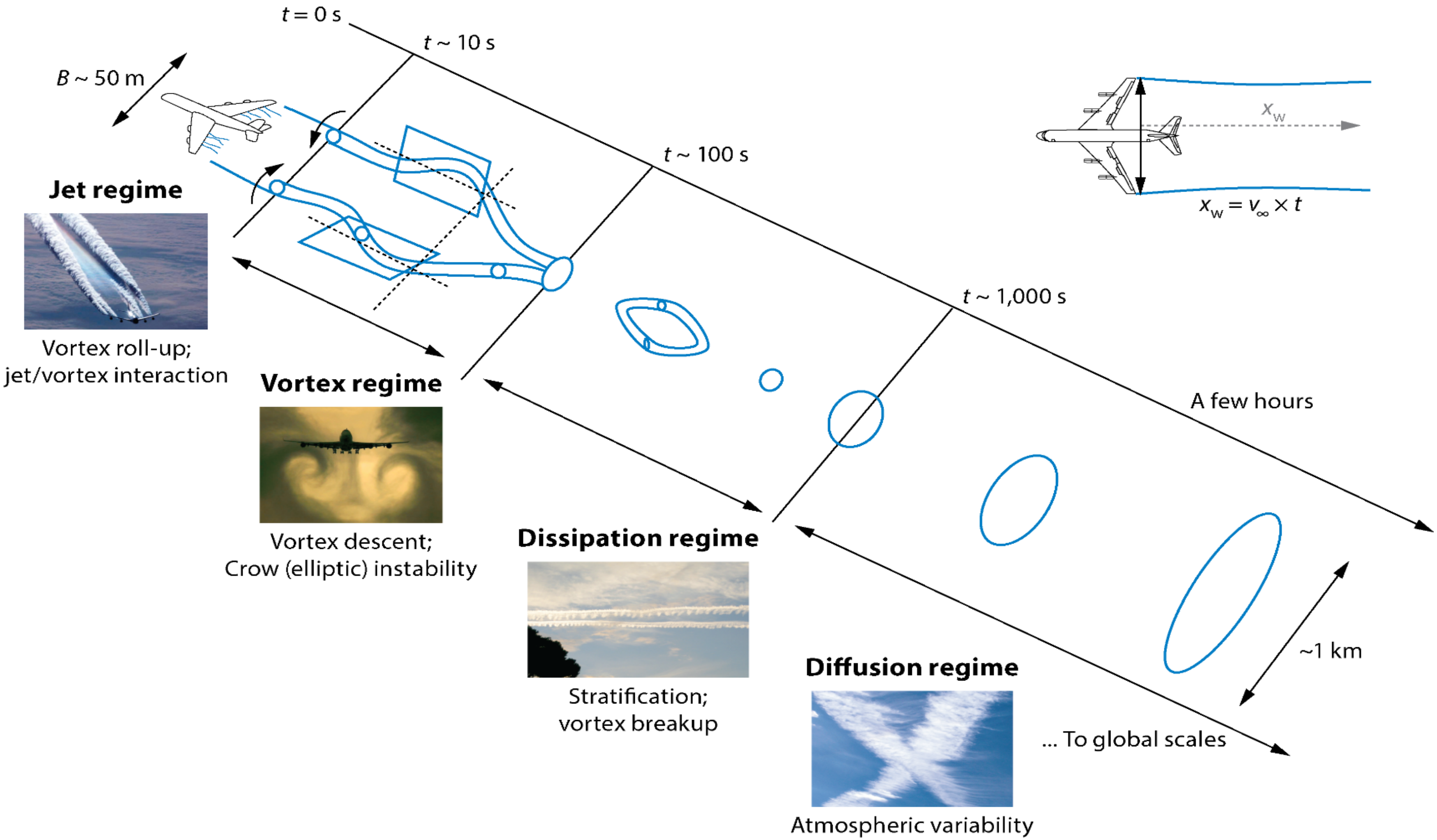






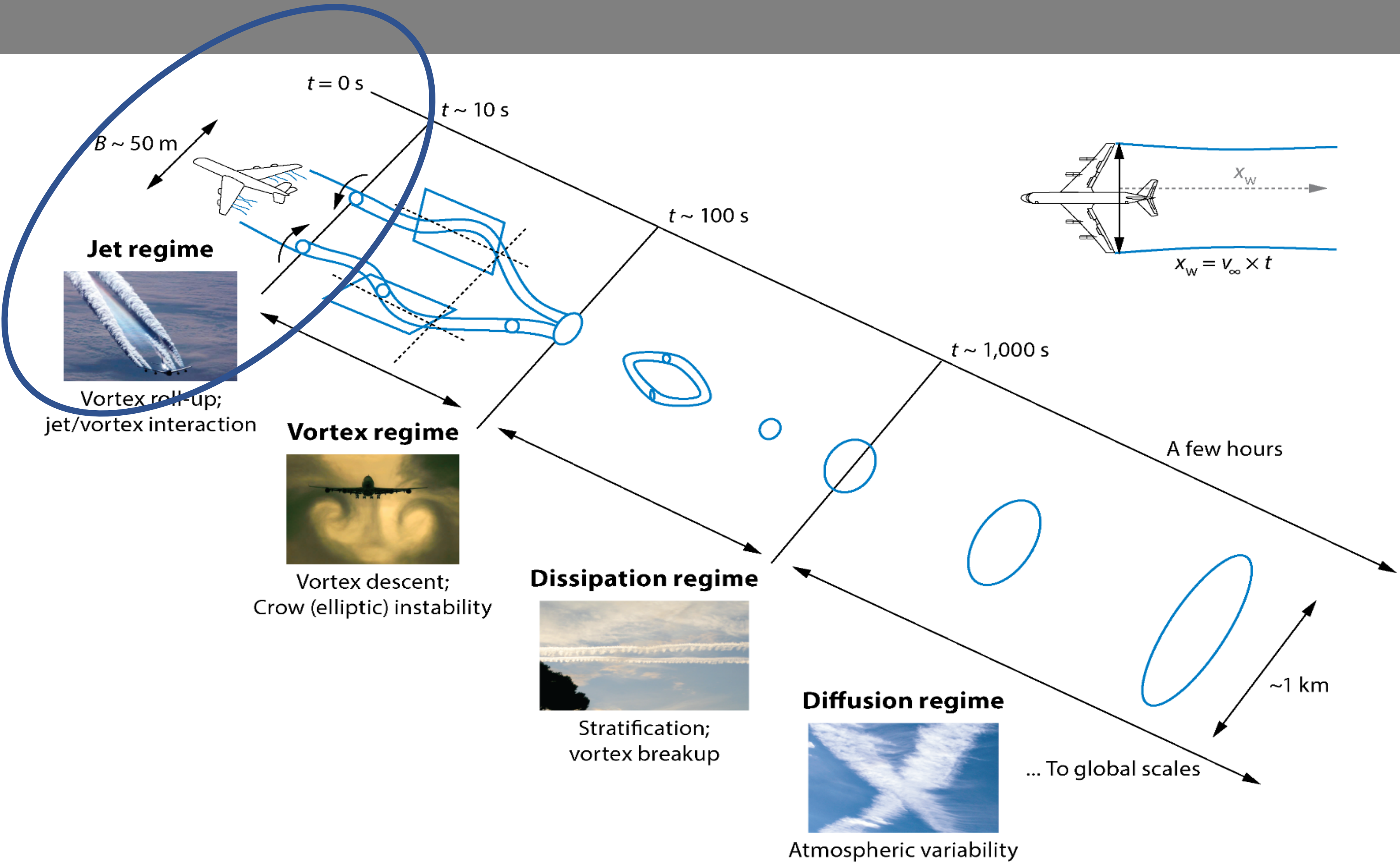


Contrail life cycle



Paoli R, Shariff K. 2016.
Annu. Rev. Fluid Mech. 48:393–427

Jet regime – ice nucleation



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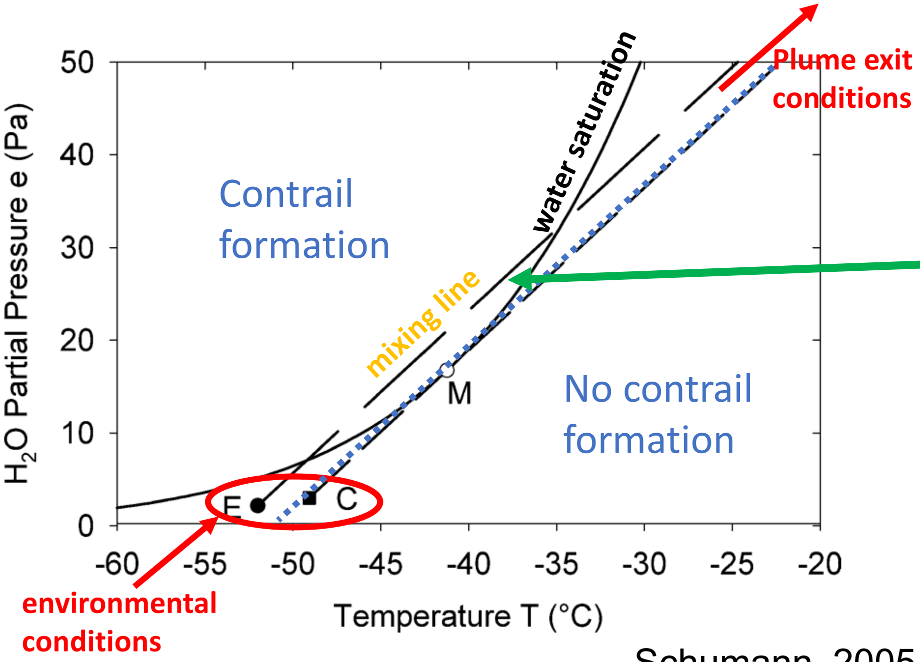
Jet regime – contrail formation - ice nucleation



Schumann, 2005

Slope of mixing line

$$G = EI_{\mathrm{H2O}} p c_p / [\varepsilon Q (1 - \eta)]$$

Propulsion efficiency

$$\eta = FV / (m_f Q)$$

EI_{H2O}: H_2O emission index Q: specific heat of combustion

η: overall propulsion efficiency p: ambient pressure

ε = 0.622: ratio of molar masses water vapour and dry air

c_p: specific heat capacity m_f: fuel flow F: thrust

V: air speed of aircraft

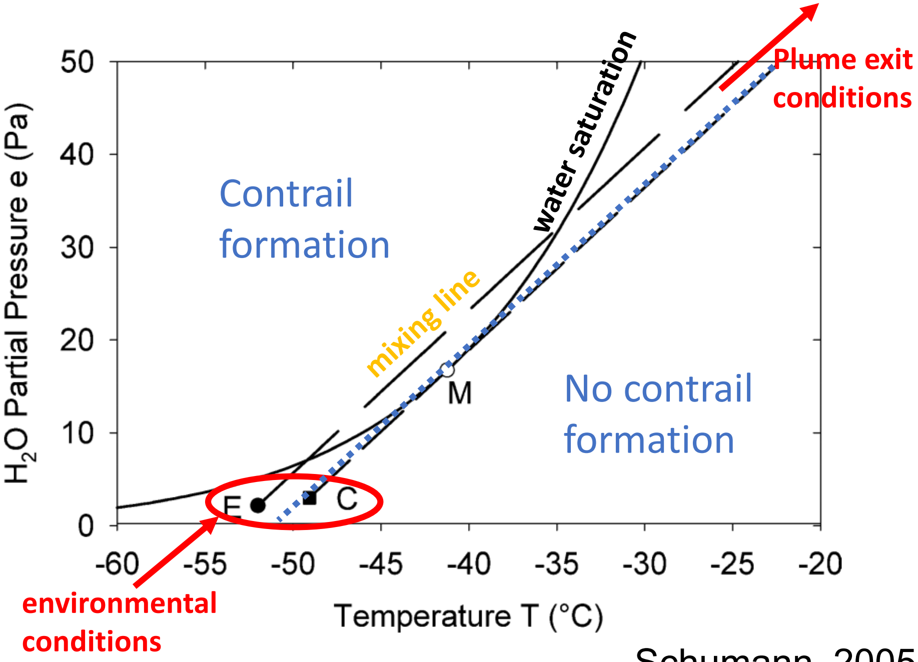
Contrail formation when plume conditions exceed water saturation.

Water saturation – droplet formation

Exhaled breath

Condensation of Exhaled Breath (the temperature was around 11°C and the RH was about 90%). Note that the water vapor begins to condense only after it mixed with enough outside air, such that it could reach a RH of 100%, when the air cooled to about 32°C.

Jet regime – contrail formation - ice nucleation



Schumann, 2005

Contrail formation when plume conditions exceed water saturation.
Contrail persists when ambient air ice supersaturated.

Slope of mixing line

$$G = EI_{\mathrm{H2O}} p c_p / [\varepsilon Q (1 - \eta)]$$

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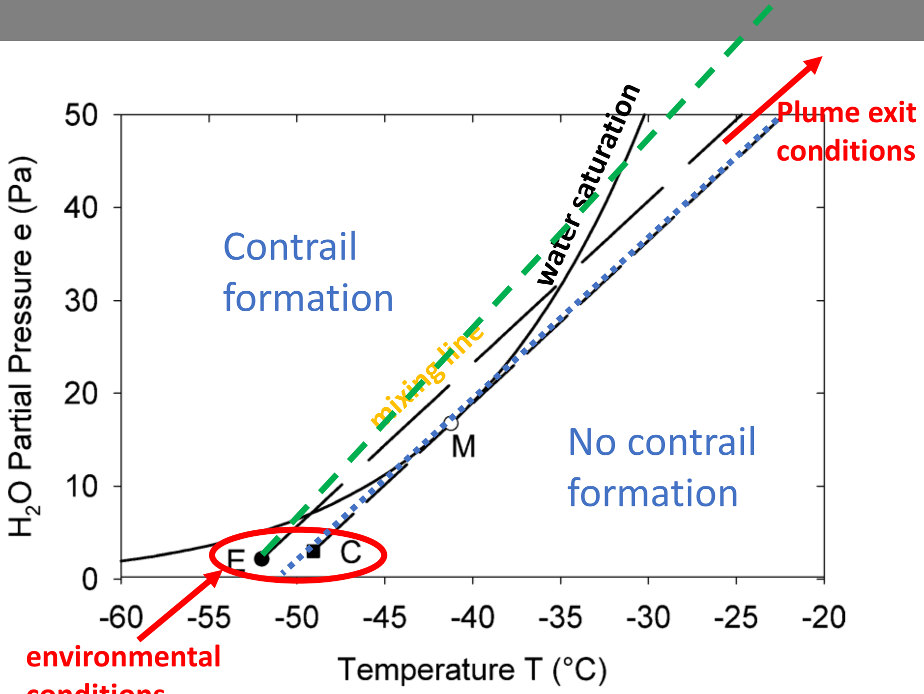

Plume exit conditions

environmental conditions

Schumann, 2005

Slope of mixing line

$$G = EI_{\mathrm{H2O}}\, p c_p / [\varepsilon Q (1-\eta)]$$

Propulsion efficiency

$$\eta = FV/(m_f Q)$$

EI_{H2O}: H_2O emission index

Q: specific heat of combustion

η: overall propulsion efficiency

p: ambient pressure

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c_p: specific heat capacity

m_f: fuel flow

F: thrust

V: air speed of aircraft

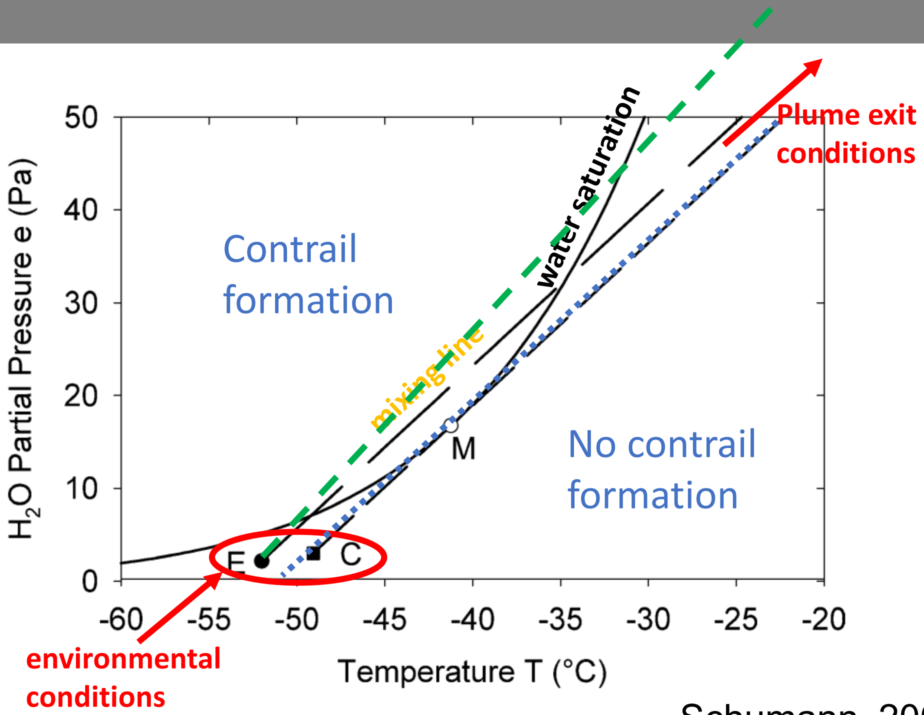
Contrail formation when plume conditions exceed water saturation.

Contrail persists when ambient air ice supersaturated.

The higher the propulsion efficiency the higher the temperature at which contrails can form.

Condensation of Exhaled Breath (the temperature was around 11°C and the RH was about 90%). Note that the water vapor begins to condense only after it mixed with enough outside air, such that it could reach a RH of 100%, when the air cooled to about 32°C.

Jet regime – contrail formation - ice nucleation



Schumann, 2005

Contrail formation when plume conditions exceed water saturation.

Contrail persists when ambient air ice supersaturated.

Many ice crystals form when ambient temperature are well below the formation threshold temperature

Slope of mixing line

$$G = EI_{\mathrm{H2O}}\, p c_p / \left[\varepsilon Q (1 - \eta) \right]$$

Propulsion efficiency

$$\eta = FV / (m_f Q)$$

EI_{H2O}: H_2O emission index Q: specific heat of combustion

η: overall propulsion efficiency p: ambient pressure

ε = 0.622: ratio of molar masses water vapour and dry air

c_p: specific heat capacity m_f: fuel flow F: thrust

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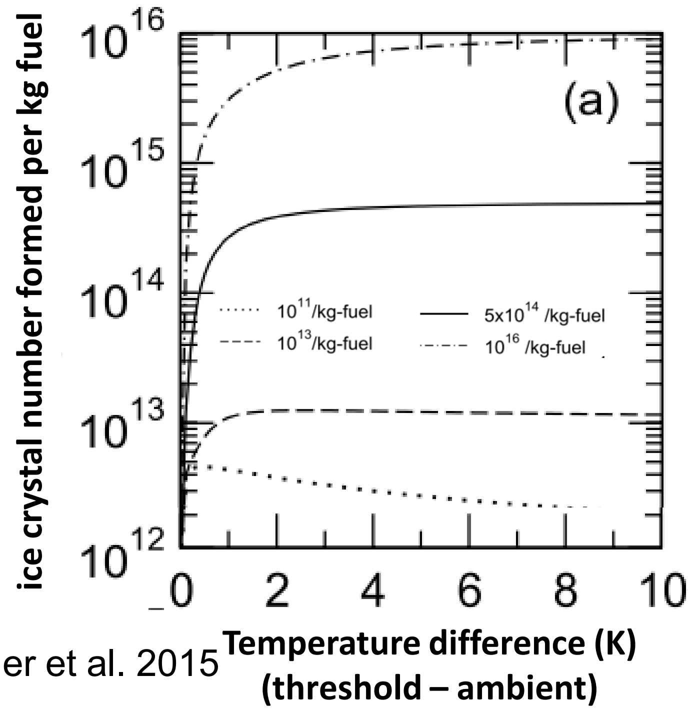
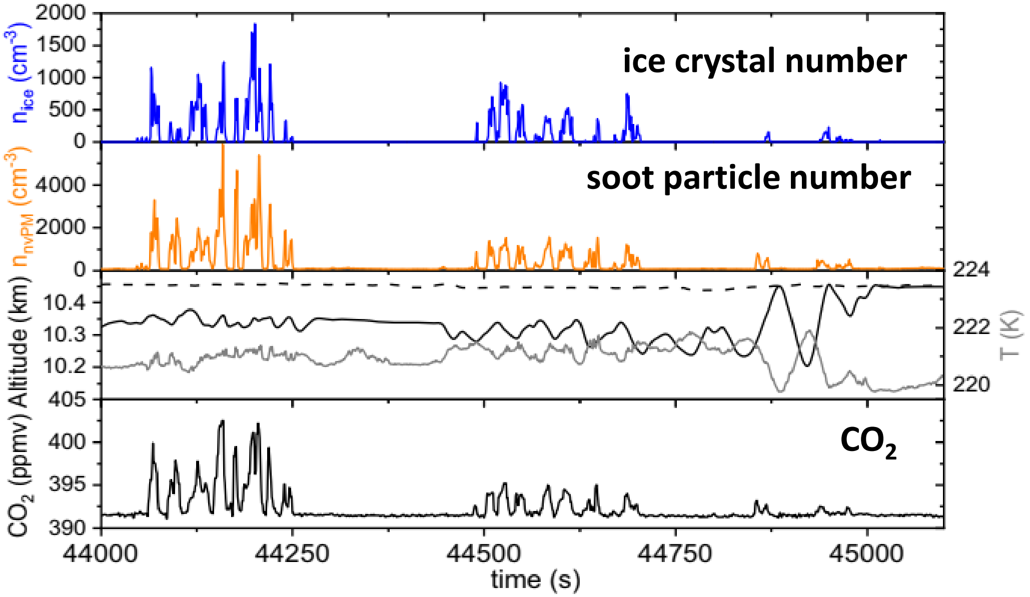
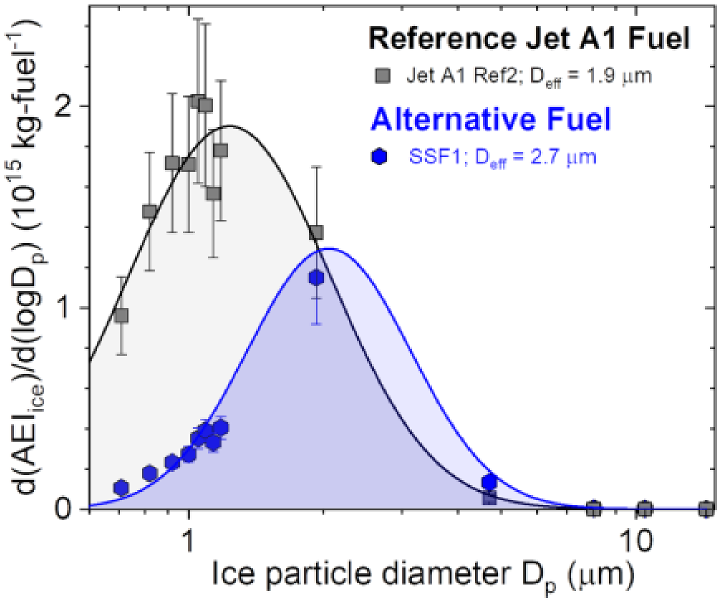


Kärcher et al. 2015

Jet regime – ice nucleation

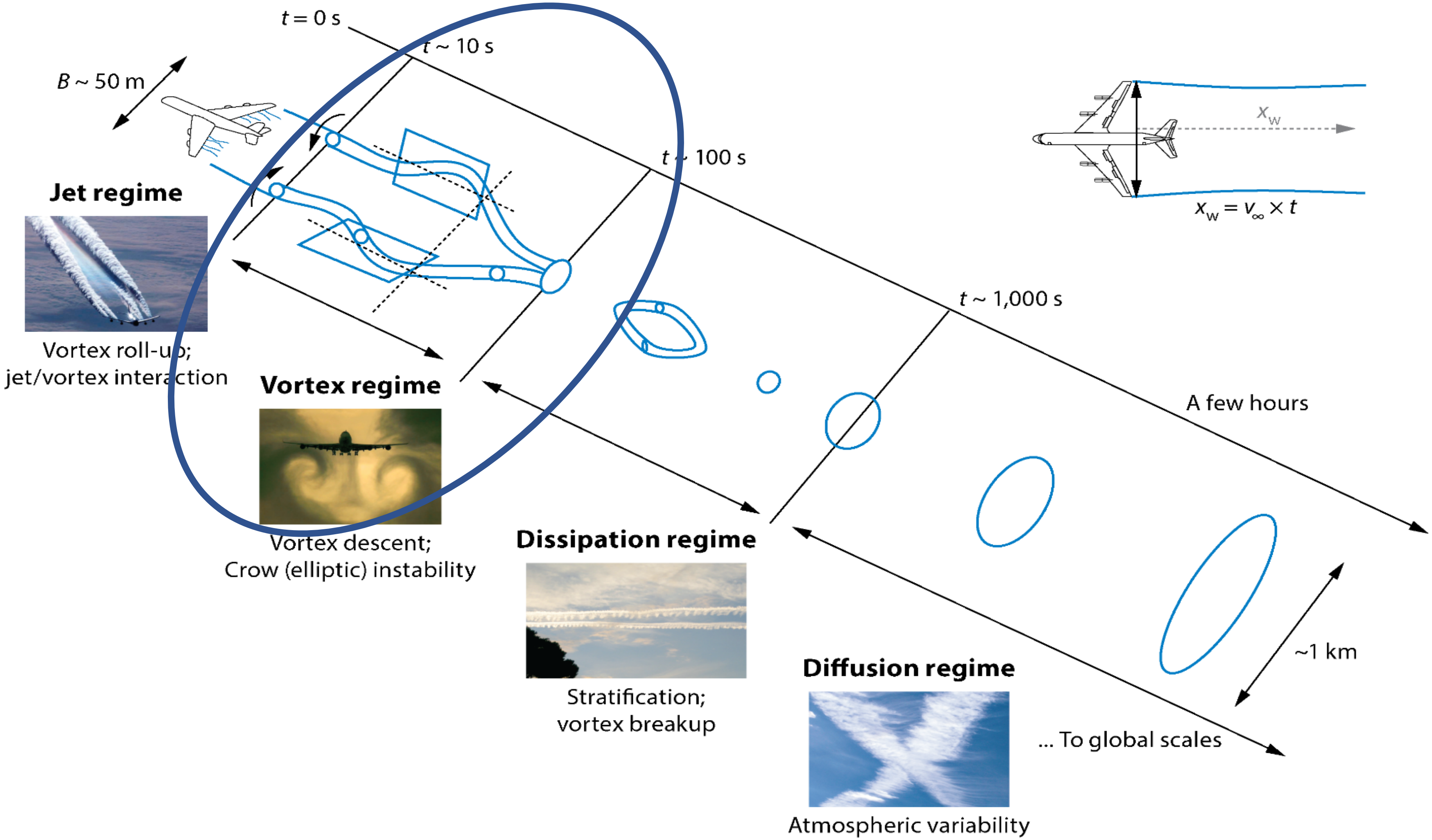
Voigt et al., 2021





Ice number concentrations and sizes depend on soot number emission → varies with fuel type.

Vortex phase – sublimation of ice crystals



Paoli R, Shariff K. 2016.
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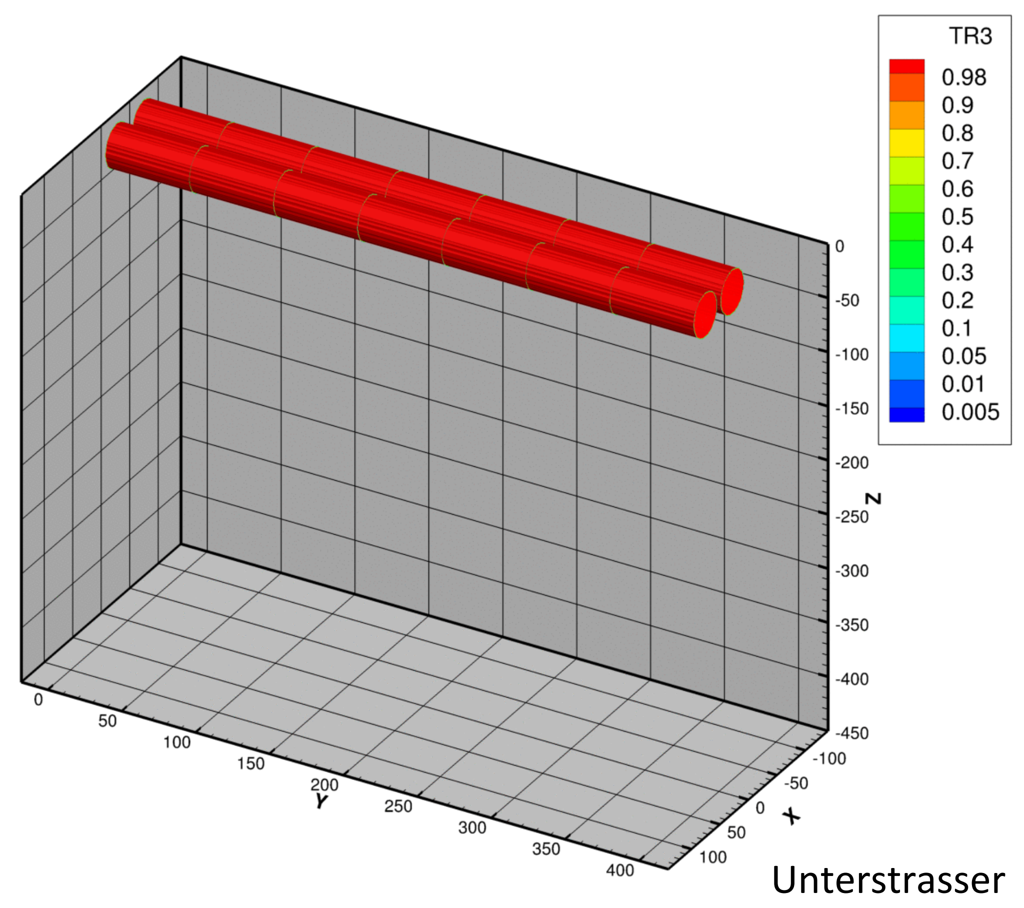
Vortex phase – sublimation of ice crystals

Simulation of wake vortex evolution (descent and break-up) and contrail ice microphysics

EULAG-LCM: 3D-LES with Lagrangian ice microphysics



Unterstrasser

Vertical expansion of contrail during the vortex phase

→300m-500m in a few minutes

Sinking of vortex

→ adiabatic heating

→ decrease of relative humidity

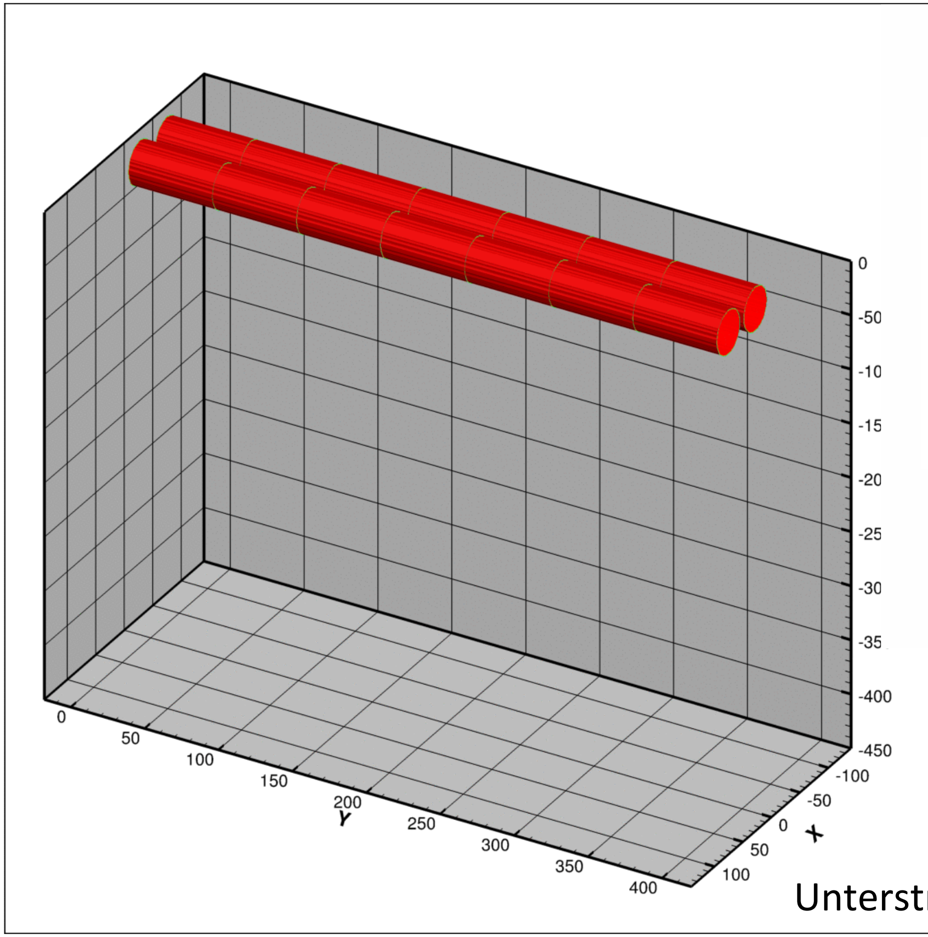
→ sublimation and ice crystal loss

The warmer and dryer the atmosphere the more ice crystals are lost.

Vortex phase – sublimation of ice crystals

Simulation of wake vortex evolution (descent and break-up) and contrail ice microphysics

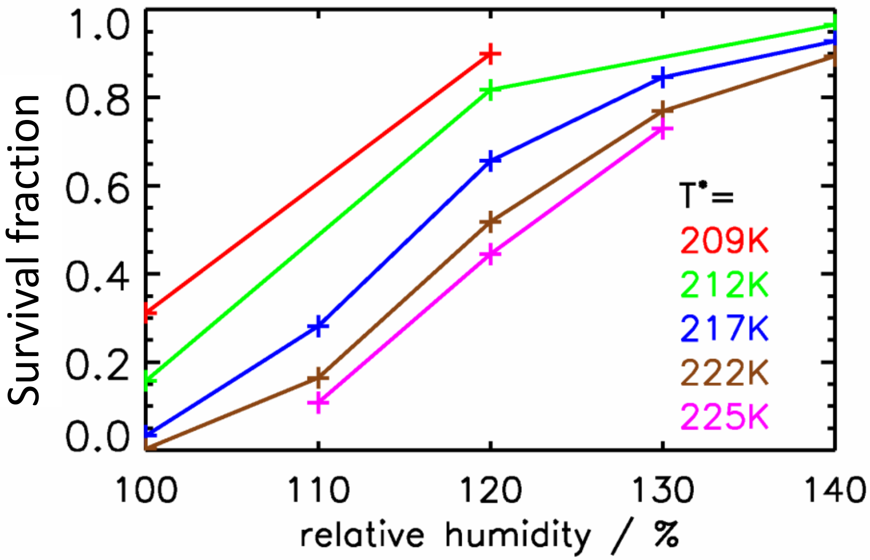
EULAG-LCM: 3D-LES with Lagrangian ice microphysics



Unterstrasser

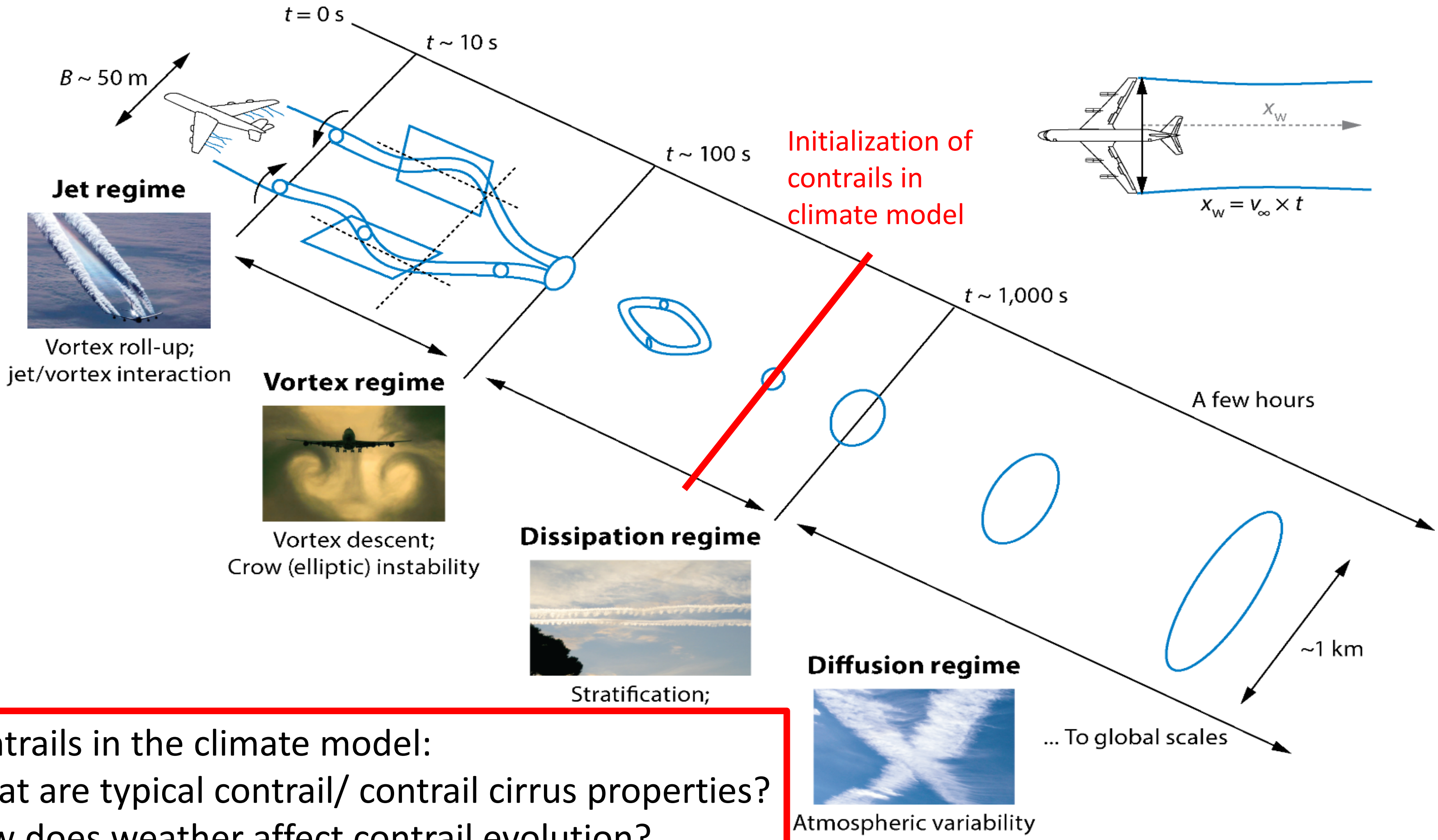
Unterstrasser, JGR, 2014

Fraction of surviving ice crystals



The warmer and dryer the atmosphere the more ice crystals are lost.

Diffusion regime – impact of atmospheric variability

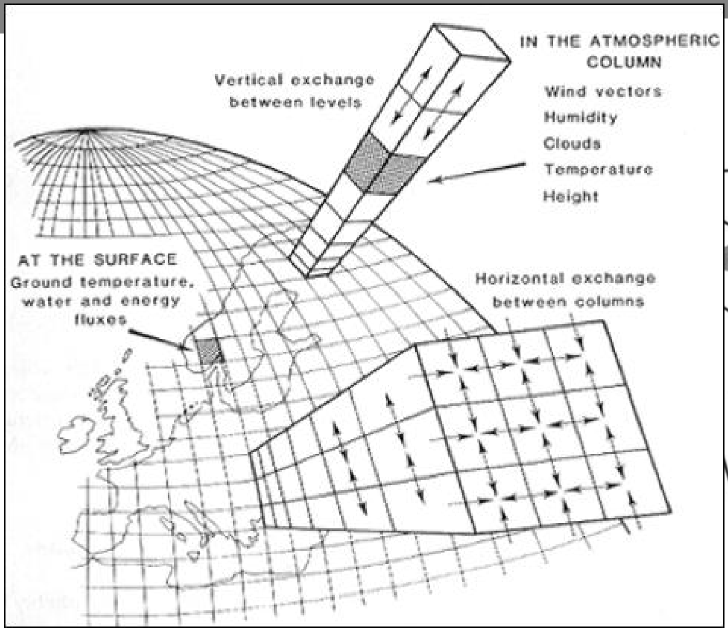


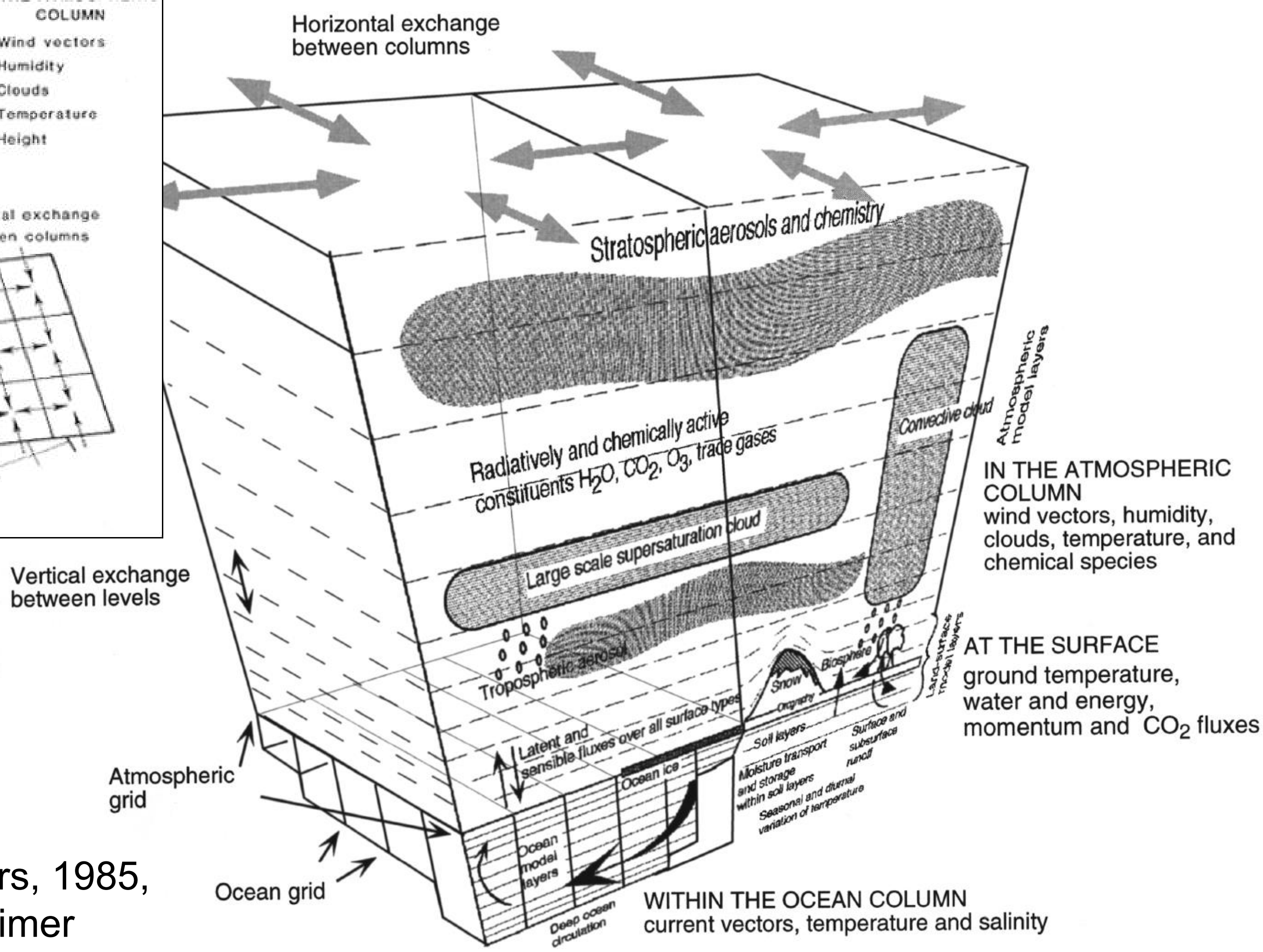
Initialization of contrails in climate model

Contrails in the climate model:
What are typical contrail/ contrail cirrus properties?
How does weather affect contrail evolution?
What effect do contrails have on water, heat and radiation budget?

Paoli R, Shariff K. 2016.
Annu. Rev. Fluid Mech. 48:393–427

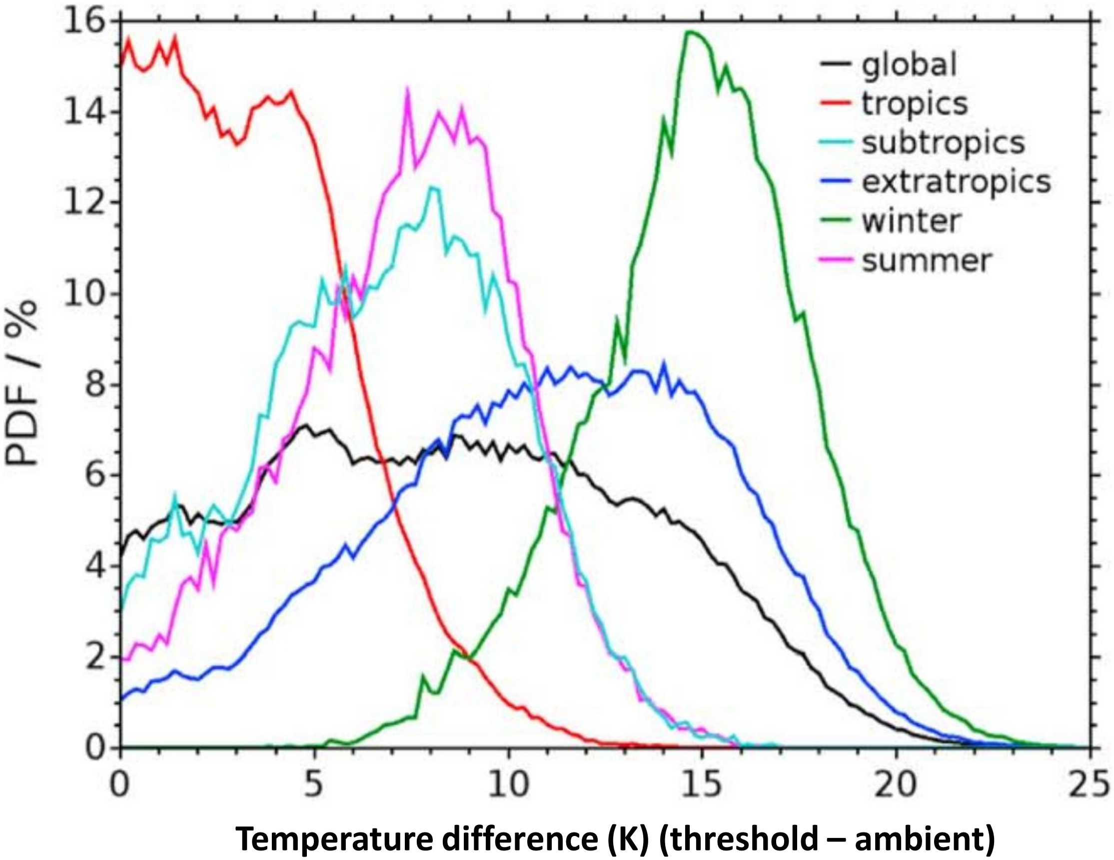
Climate model





McGuffie, Henderson-Sellers, 1985,
A Climate Modelling Primer

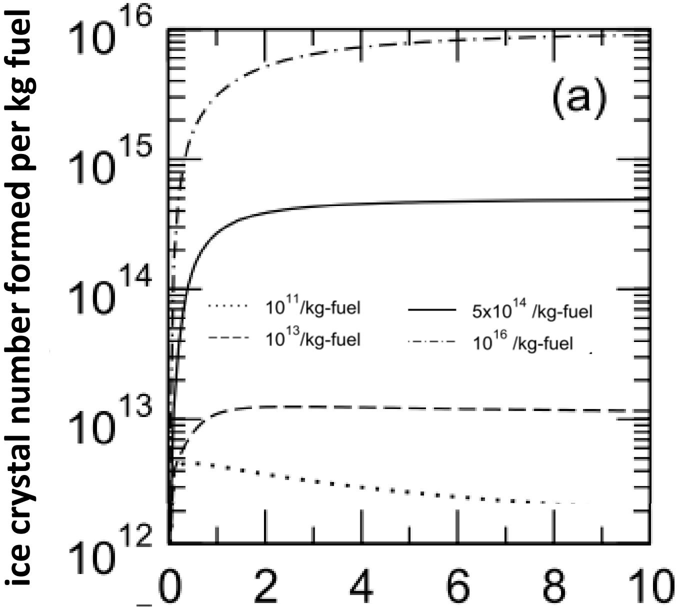
Parameterization - ice nucleation



Difference between formation threshold and ambient temperatre (Ice nucleation) varies strongly with region and seasons

Bier and Burkhardt, JGR, 2019

Ice nucleation dependent on temperature difference between ambient air and contrail formation threshold (Kärcher et al., 2015).



Kärcher et al. 2015

Temperature difference (K) (threshold – ambient)

Model: ECHAM5-CCMod

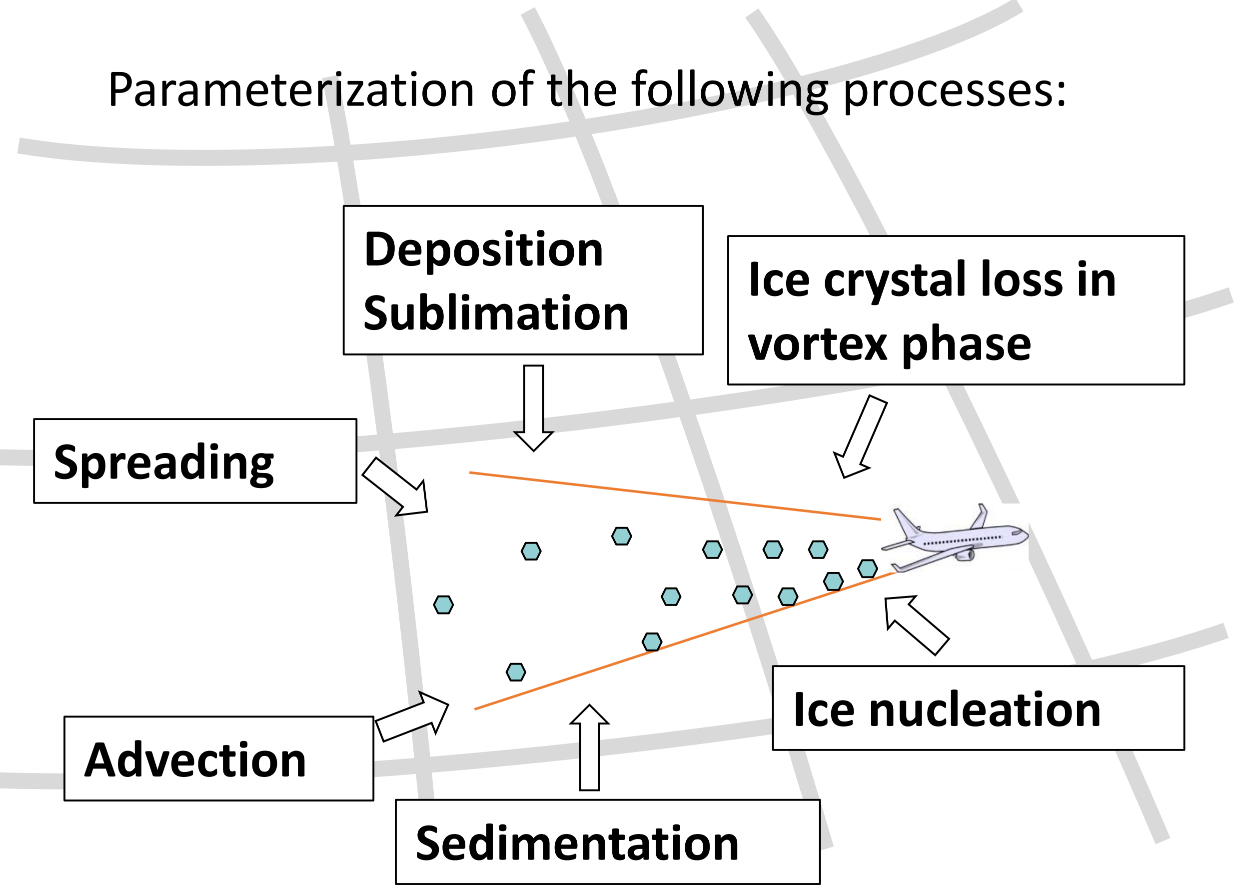
ECHAM 5 - German community climate model (T42/L39)
CCMod - Simulation of a new cloud class: persistent contrail cirrus

Microphysical 2-moment-scheme

prognostic treatment of
- contrail cirrus volume,
- IWC
- ice particle number concentration …..

evolution in cloud-free ice supersaturated areas (fractional grid boxes)

Parameterization of the following processes:



Deposition
Sublimation

Ice crystal loss in vortex phase

Spreading

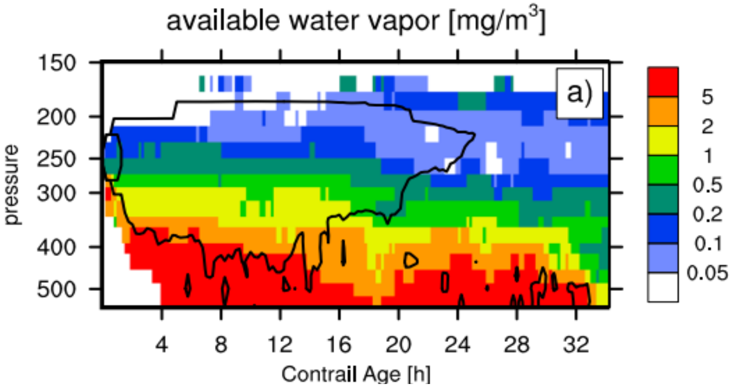
Ice nucleation

Advection

Sedimentation

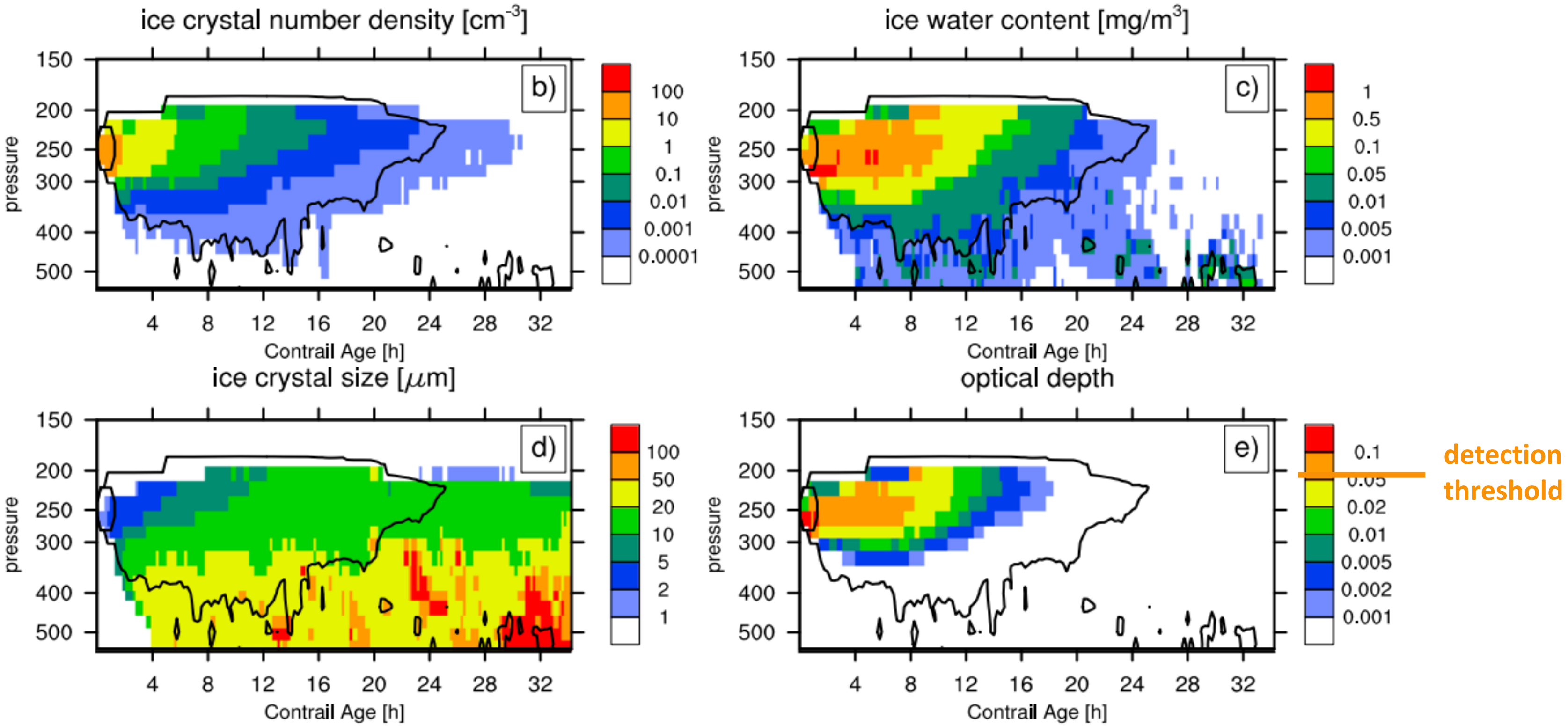
Burkhardt and Kärcher, JGR, 2009; Bock and Burkhardt, JGR, 2016a; Bier and Burkhardt, to be submitted

Interaction with synoptic variability: Evolution of a contrail cirrus cluster



Initialization of a long lived contrail cirrus cluster over Northern America

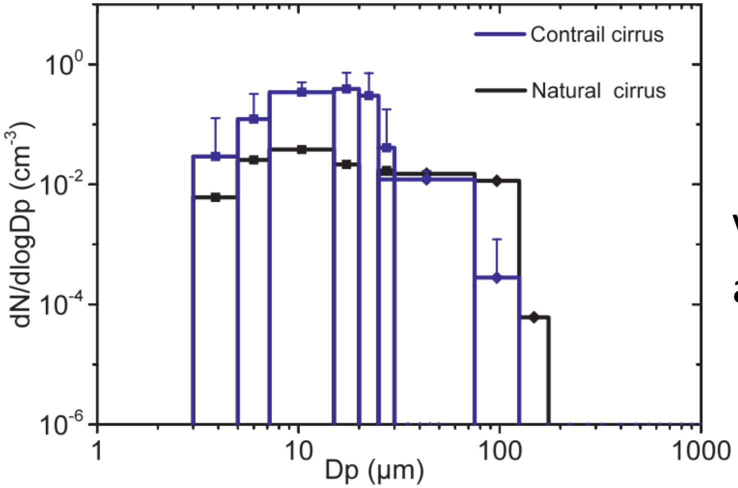
Bock and Burkhardt, JGR, 2016a



Measurements of aged contrails

Satellite imagery can provide estimates of contrail optical depth and distribution but geostationary satellites have often a too low resolution to resolve thin contrails.

Ice crystal size distribution cirrus - contrail



Voigt et al., 2017

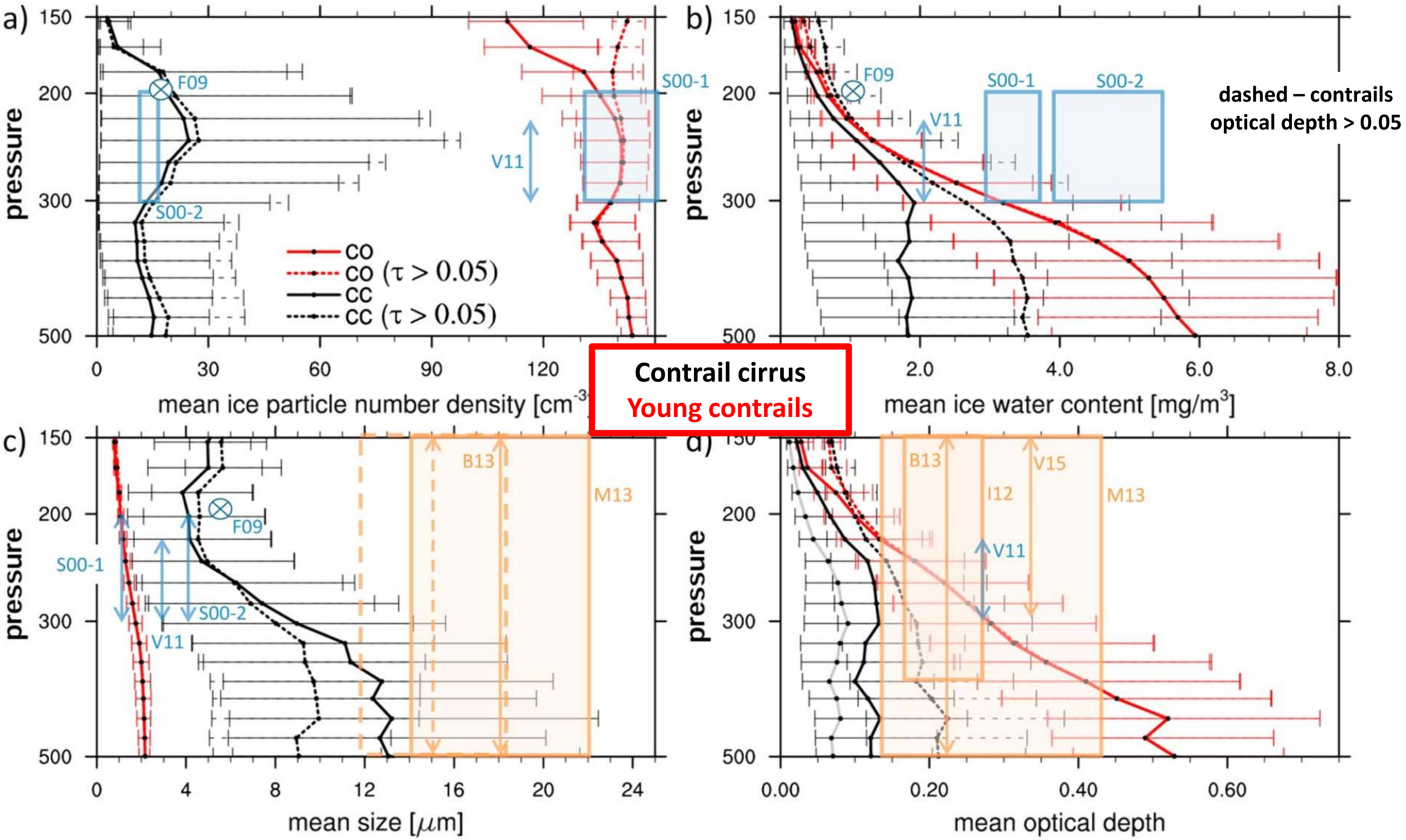
Ice crystal size distribution of aged contrails (3h) is still significantly different to the size distribution of natural cirrus.

Cirrus has lower number of ice crystals and larger sizes.

Bugliaro et al. to be submitted

Evaluation contrail properties with observations

Bock and Burkhardt, JGR, 2016b



dashed – contrails optical depth > 0.05

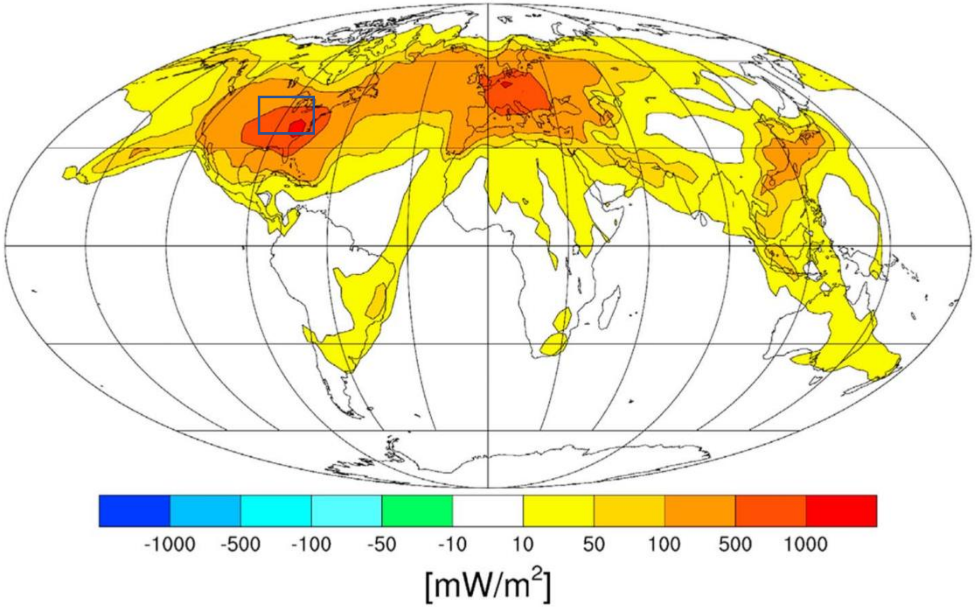
Contrail cirrus
Young contrails

S00 - Schröder et al., 2000; F09 - Febvre et al., 2009; V11 - Voigt et al., 2011

I12 - Iwabuchi et al., 2012; M13 - Minnis et al., 2013; B13 - Bedka et al., 2013; V15 - Vazquez-Navarro et al., 2015

Impact of synoptic variability on contrail cirrus radiative forcing

Contrail cirrus radiative forcing



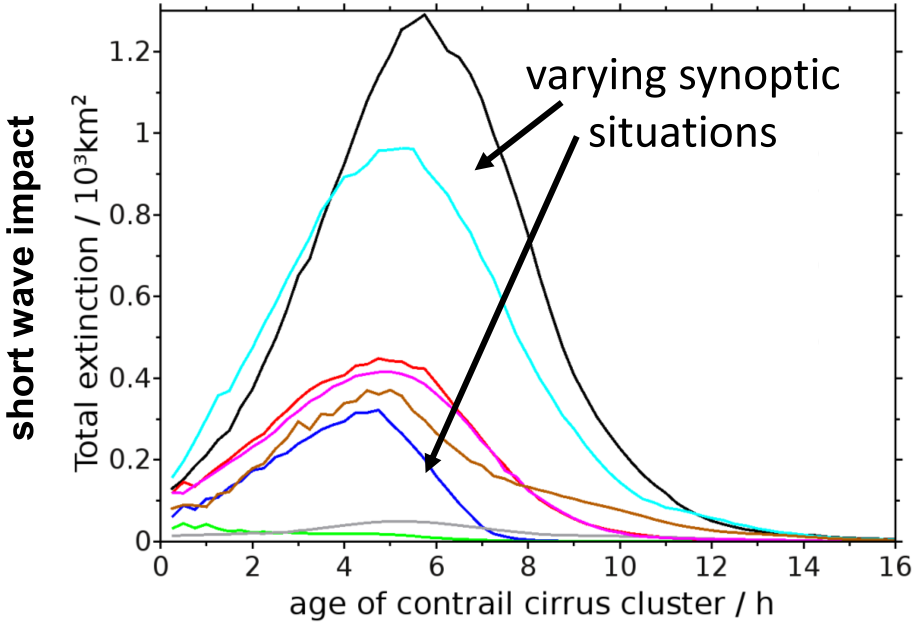
Bock and Burkhardt, JGR, 2016b

Large synoptic variability in
- **radiative impact and**
- **life times**

of contrail cirrus clusters

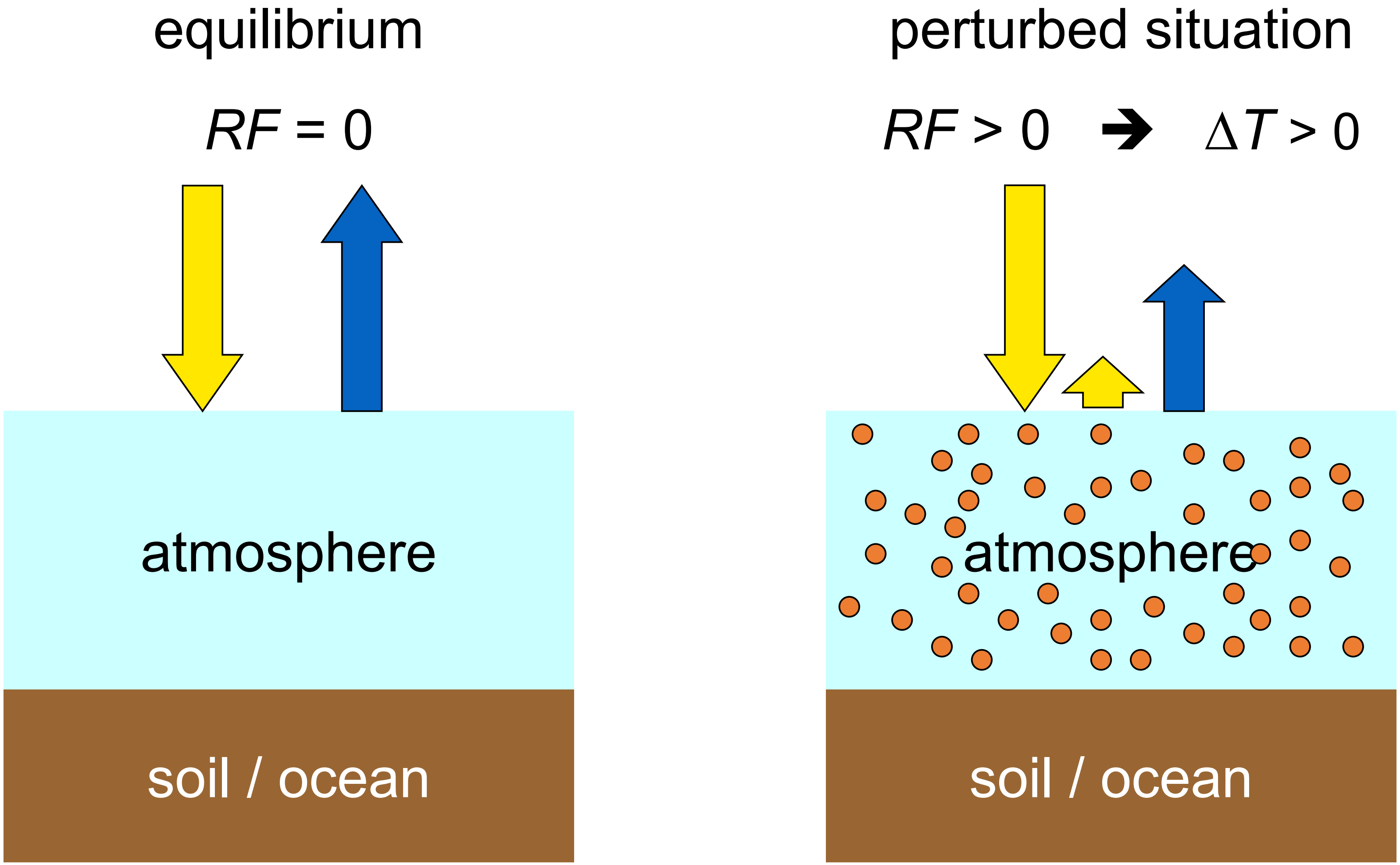
Increase in cirrus cloudiness dominated by large-scale contrail outbreak events

Variabilty of short wave impact of contrail cirrus clusters



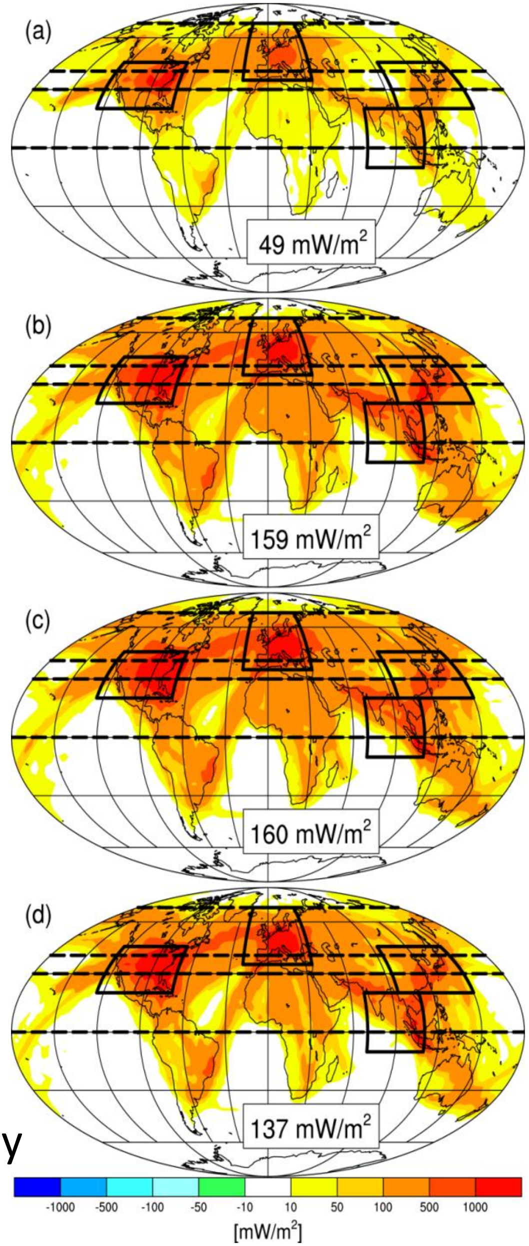
Bier, Burkhardt and Bock, JGR, 2017

What is radiative forcing (RF)? (simplified)



Optically thick ice clouds cool and optically thin ice clouds warm. Contrails warm on average. Liquid clouds usually cool.

Contrail cirrus RF



C2006 – T06

C2006 – T50
Increase in air traffic

3 fold increase in contrail cirrus radiative forcing for 2050 air traffic.

C2050 – T50
Climate change

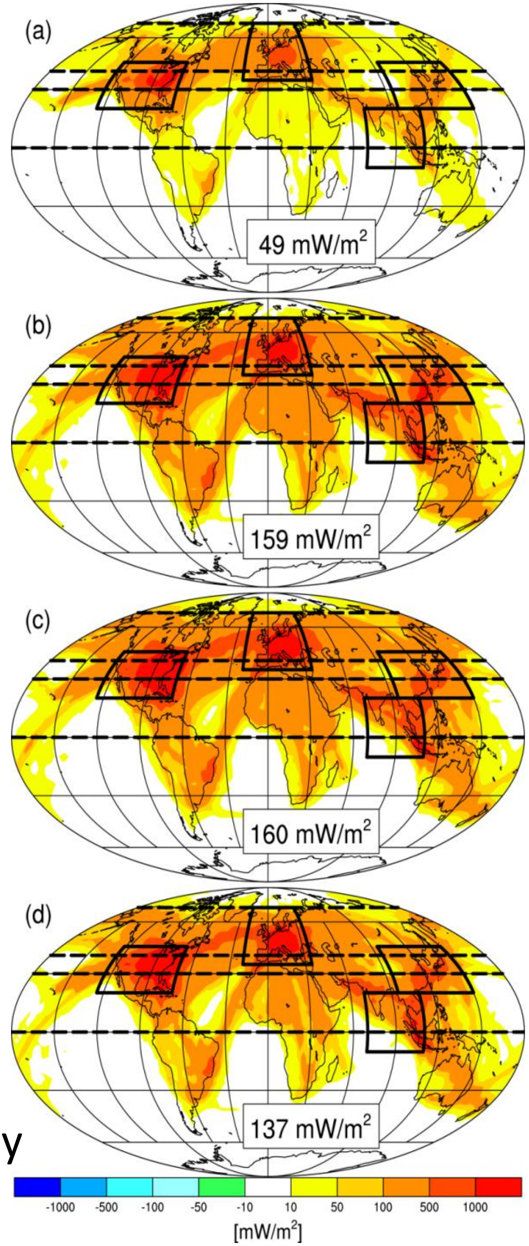
No change in contrail cirrus radiative forcing due to climate change.

C2050 – T50M
-50% soot number
Increase fuel efficiency

Small decrease in contrail cirrus radiative forcing due to reduced soot number emissions and increased fuel efficiency.

Bock and Burkhardt, ACP, 2019

Large increases in contrail cirrus radiative forcing due to increased air traffic cannot be balanced by projected decreased soot number emissions together with increased fuel efficiency!



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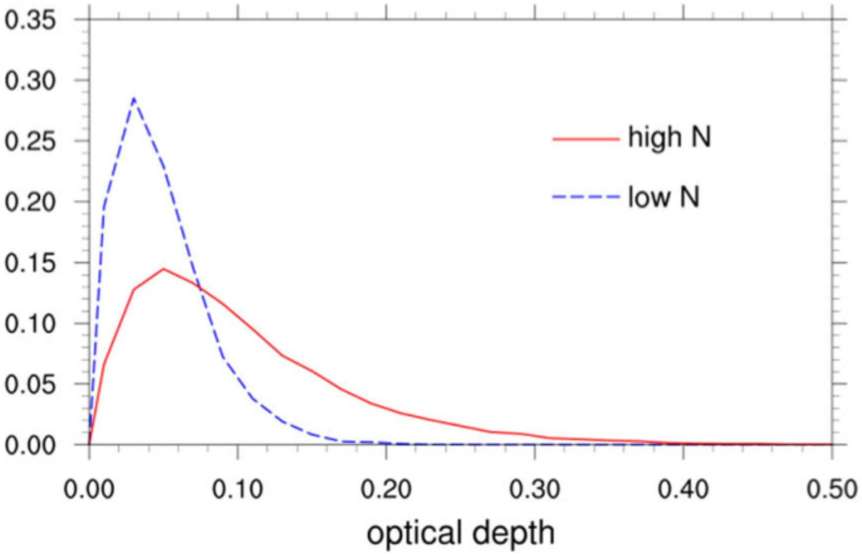
Bock and Burkhardt, ACP, 2019

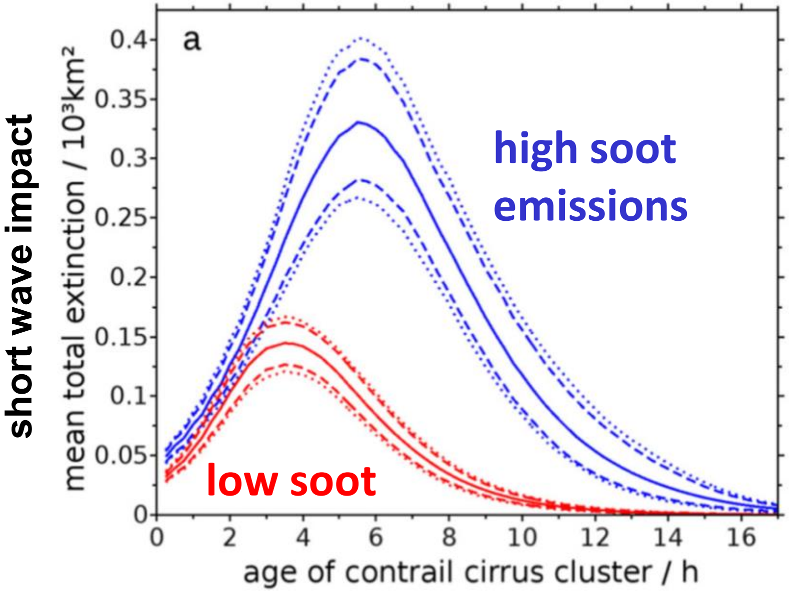
Impact of soot number emission reductions by 80% on contrail cirrus

Change in frequency of contrail cirrus optical depth over Europe



Higher probability of lower contrail cirrus optical depth

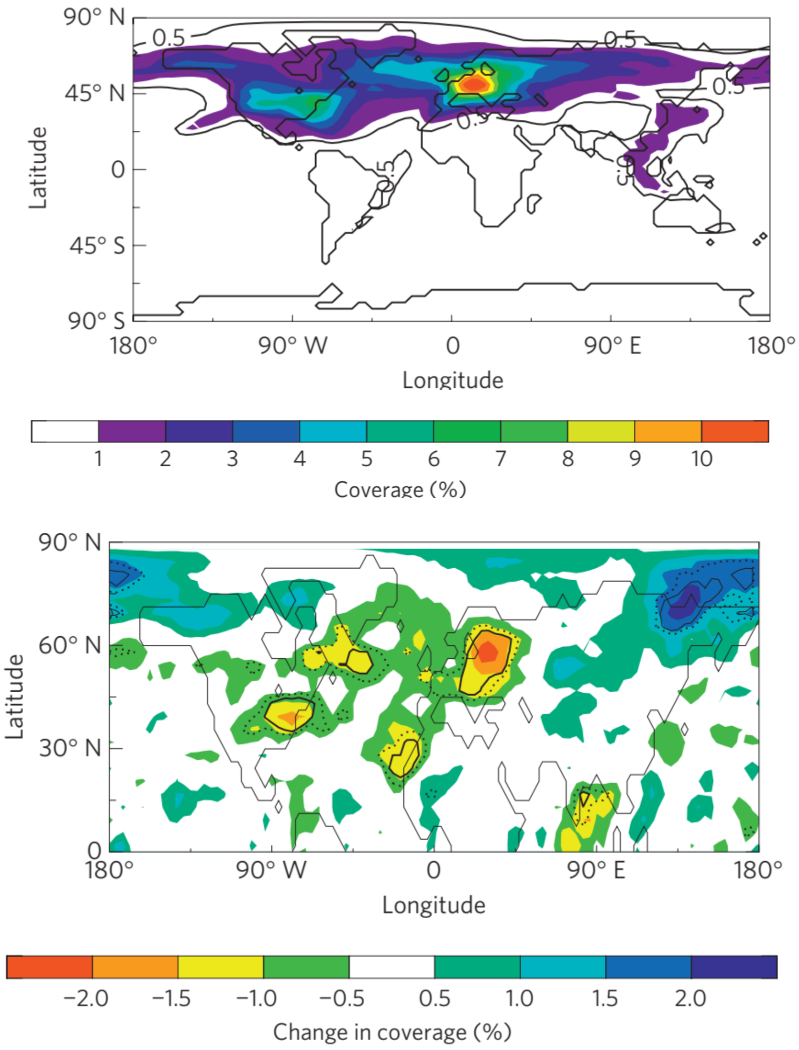
Change in short wave impact and life times



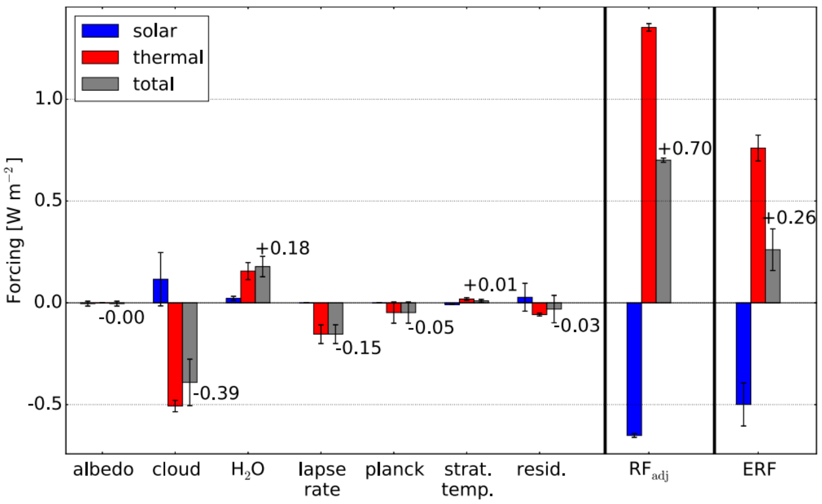
Strongly reduced life time and optical depth of contrail cirrus clusters due to reductions in soot emissions

Burkhardt et al., NPJ Climate and Atmospheric Science, 2018

Contrail cirrus RF limited by cloud adjustment



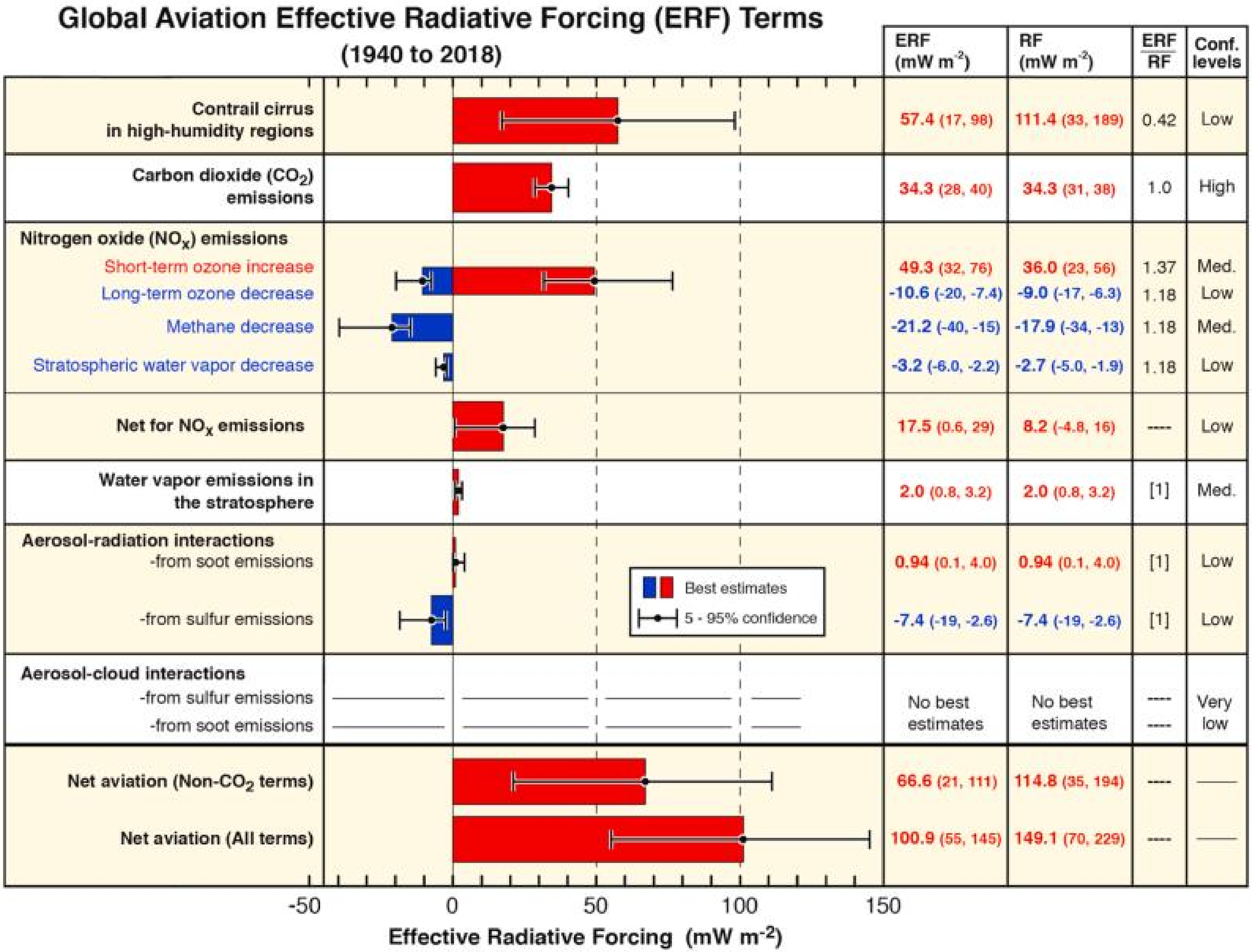
Burkhardt and Kärcher, Nature Climate Change, 2011



Bickel et al., Journal of Climate, 2020

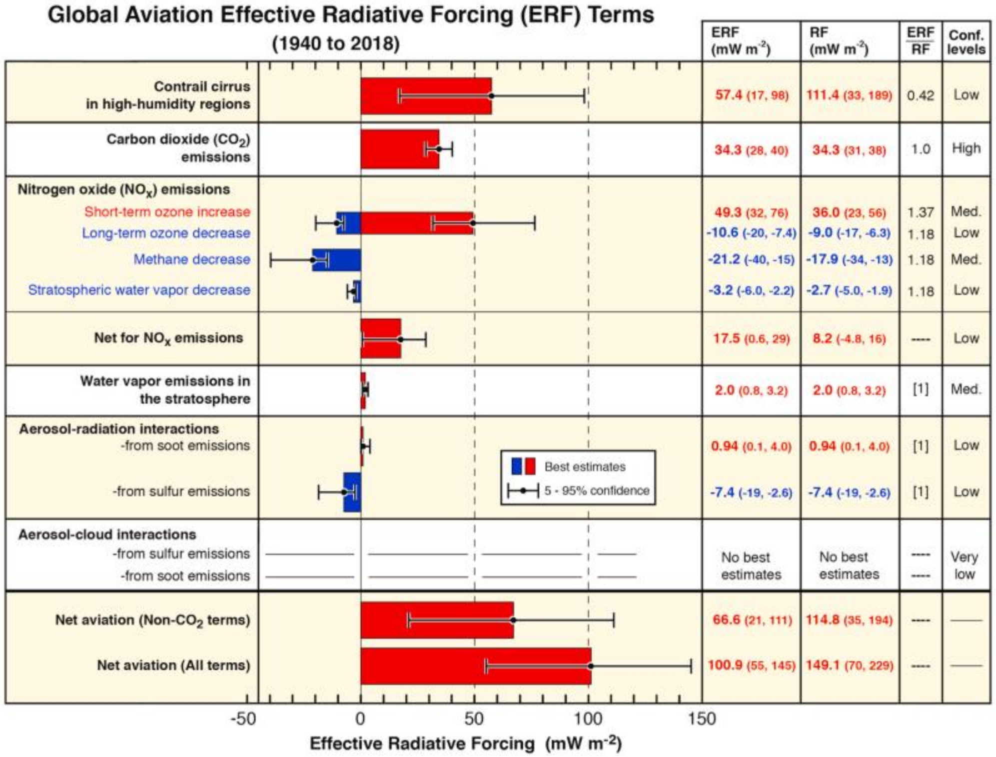
Simulating the competition between contrails and natural clouds allows to calculate the change in natural cloudiness due to the presence of contrails.

Adjustments in natural clouds may be significant – exact strength of adjustment needs to be explored further.



	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	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
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., Atmospheric Environment, 2021



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From Lee et al.: 'The uncertainties for contrail cirrus were estimated partly from expert judgement of the underlying processes ….'

Uncertainties contrail cirrus RF - ~70%:

Related to radiative response **55%**:

- model's radiative transfer scheme → 35%
- inhomogeneity of ice clouds, vertical cloud overlap, and the use of plane parallel geometry as compared to full 3D radiative transfer → 35%
- presence of very small ice crystals → 10%
- ice crystal habit → 20%
- soot cores within the contrail cirrus ice crystals - not yet quantified.

Upper-tropospheric water budget and contrail cirrus scheme **40%**

- upper-tropospheric ice supersaturation → 20%
- ice crystal number densities within young contrails. Assuming an uncertainty in average contrail ice crystal numbers after the vortex phase of about 50% → 20%
- lifetime of contrail cirrus affecting day/night coverage → 5–10%
- feedback of natural clouds – uncertainty slightly smaller than estimate → 15%

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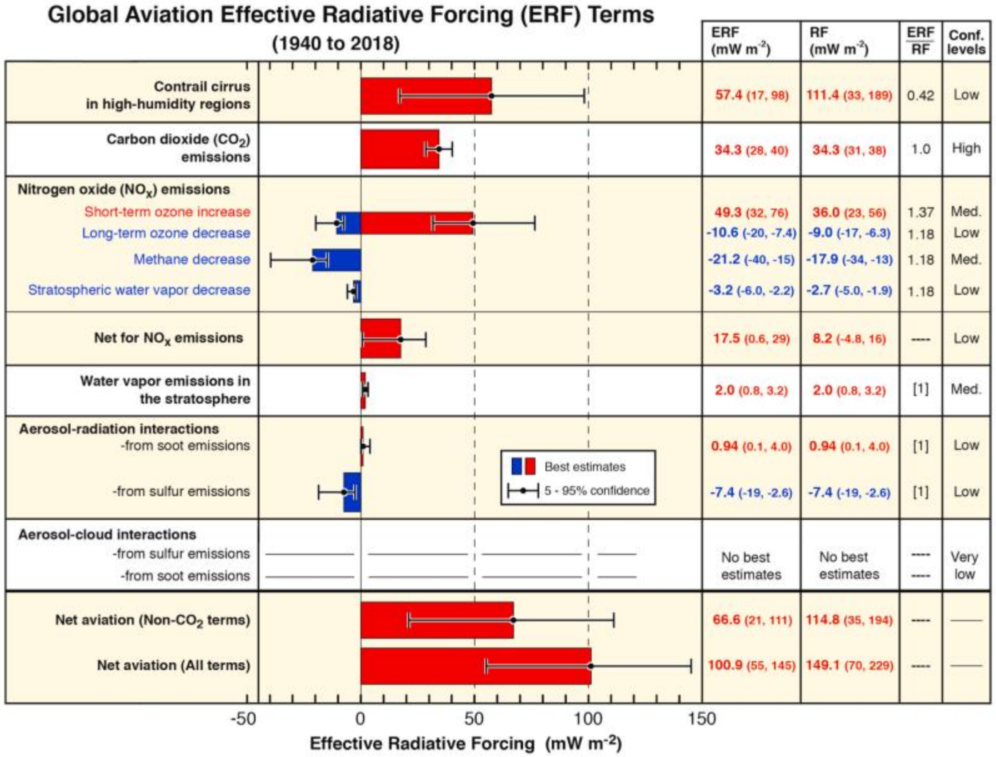
Global Aviation Effective Radiative Forcing (ERF) Terms (1940 to 2018)

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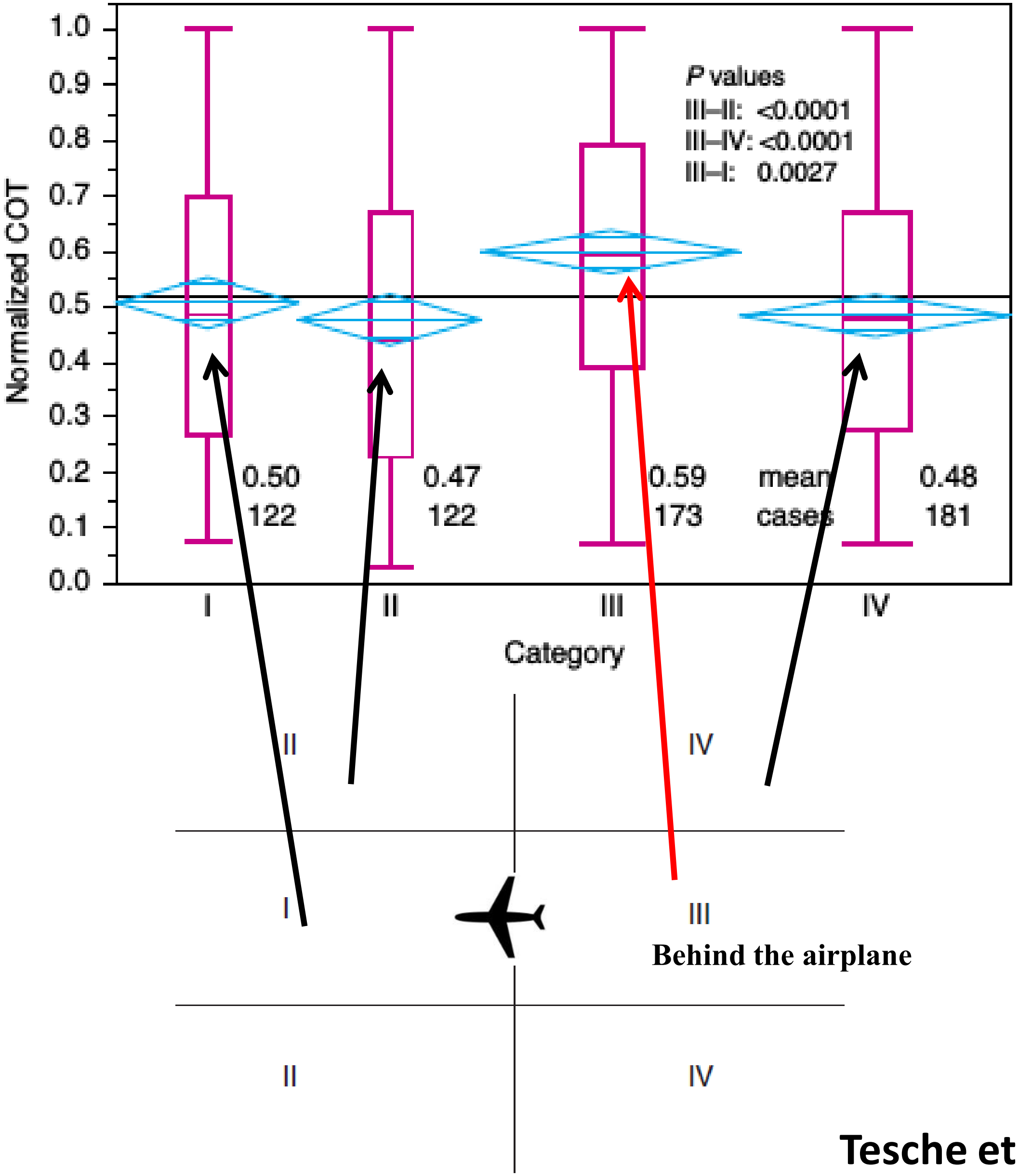
BUT are all aviation / contrail effects covered?????

Contrail induced perturbations of natural clouds



Behind the airplane

Cloud optical thickness (COT) before, behind and next to an aircraft / inferred from Calipso

Change in cloud optical depth due to air traffic within cirrus as inferred from Calipso measurements.

Changes can be detected with a lidar in space!

What is the impact of cirrus perturbations due to contrail formation?

Tesche et al., 2016

Conclusions

Contrails form when the exhaust air mixes with the cold environmental air.

Contrail ice nucleation depends on engine emissions and environmental conditions.

Properties and life times of contrails are controlled by the formation conditions and by the atmospheric development → large variability in properties and life time.

Contrail cirrus warm the atmosphere on average.

Contrail cirrus is the largest aviation related forcing component.

Uncertainty of radiative forcing estimates that are connected with cloud processes is very large.

Short life time of contrails makes them ideal objects for mitigation efforts.

When discussing the aviation climate impact or mitigation options we need to remember that not all effects have been estimated yet.

Thank you for your attention!

Thank you to:

Lisa Bock, Andreas Bier and Pooja Verma

Simon Unterstrasser, Luca Bugliaro, Tina Jurkat-Witschas, Martin Wirth

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