Contrails, contrail prediction, contrail avoidance

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What are contrails and how do they form?

Photo: D. Klatt, Oldenburg

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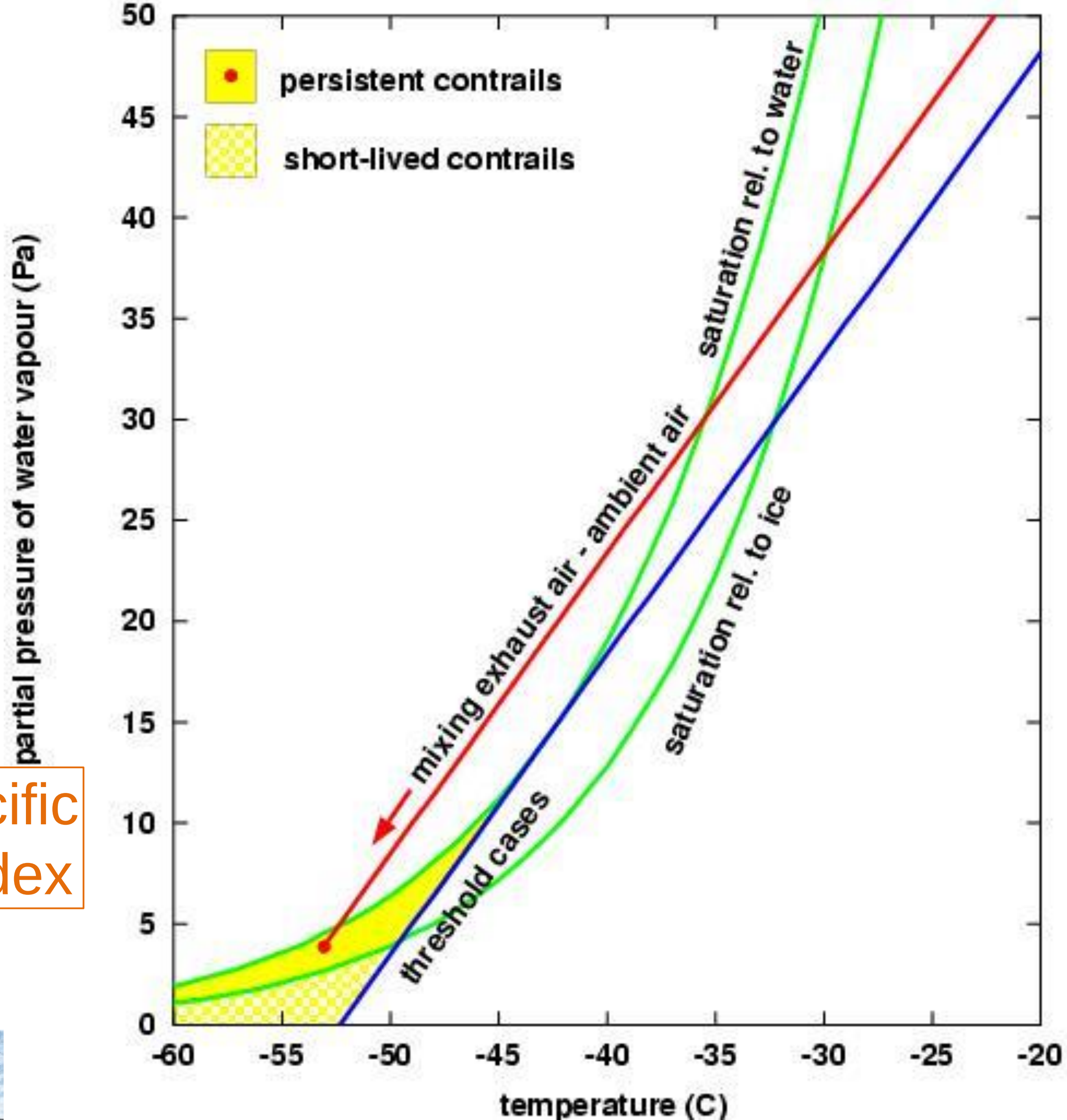
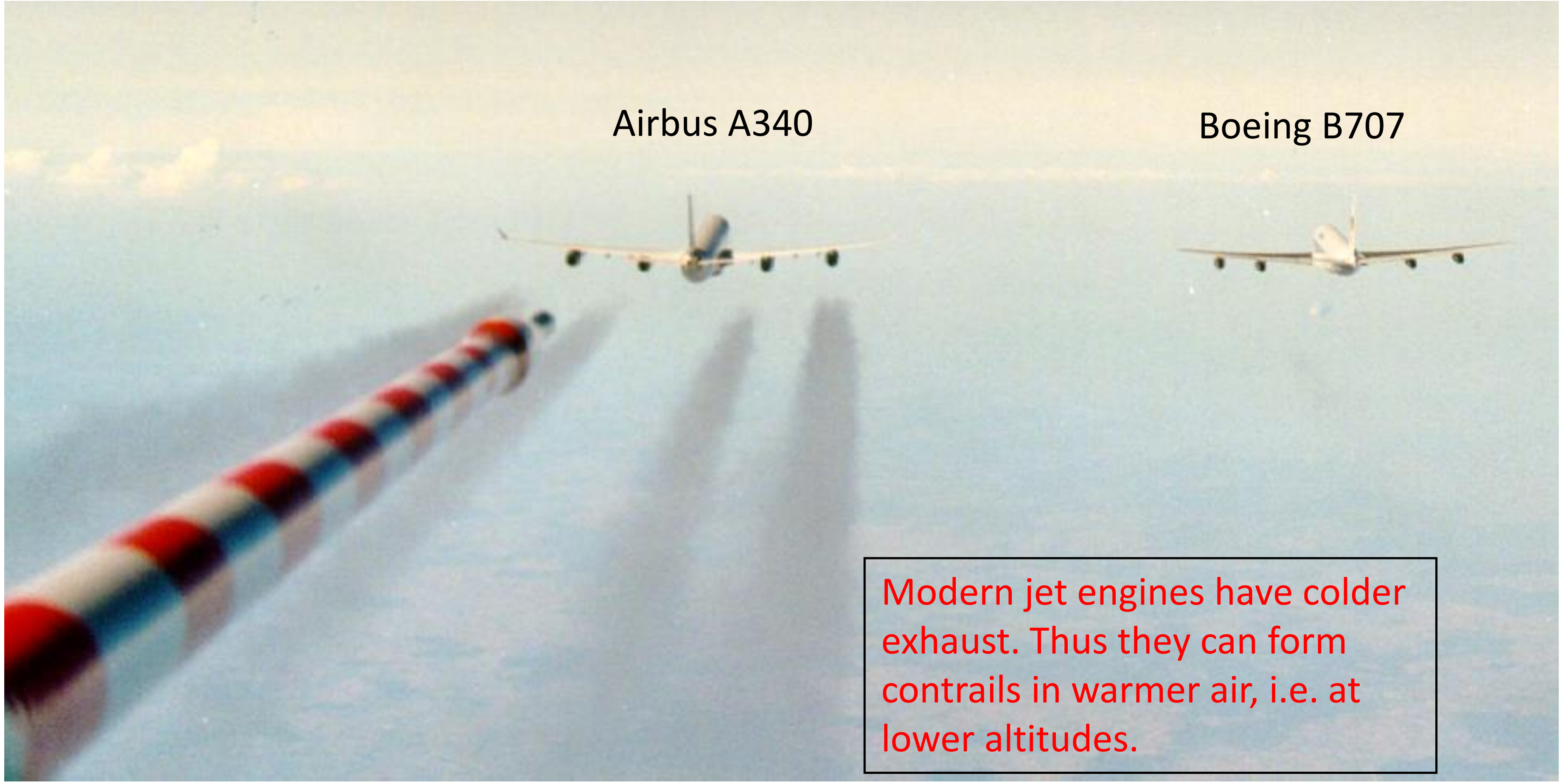
What are contrails and how do they form?

- Combustion of kerosene leads to emission of mainly carbon dioxide and water vapour
- The hot exhaust plume expands and mixes isobarically with cold ambient air
- If the mixture gets supersaturated wrt liquid water, water vapour condenses to droplets and freezes in the cold environment. A contrail forms.

$$G = \frac{c_p p}{\varepsilon}\frac{EI_{H2O}}{Q(1-\eta)} = \overbrace{\frac{c_p}{\varepsilon}}^{\text{const}}\underbrace{p}_{\text{atmosphere}}\overbrace{\frac{1}{(1-\eta)}}^{\text{aircraft/engine}}\underbrace{\frac{EI_{H2O}}{Q}}_{\text{energy-specific emission index}}$$



A contra-intuitive consequence:
modern aircraft produce more contrails than old ones!



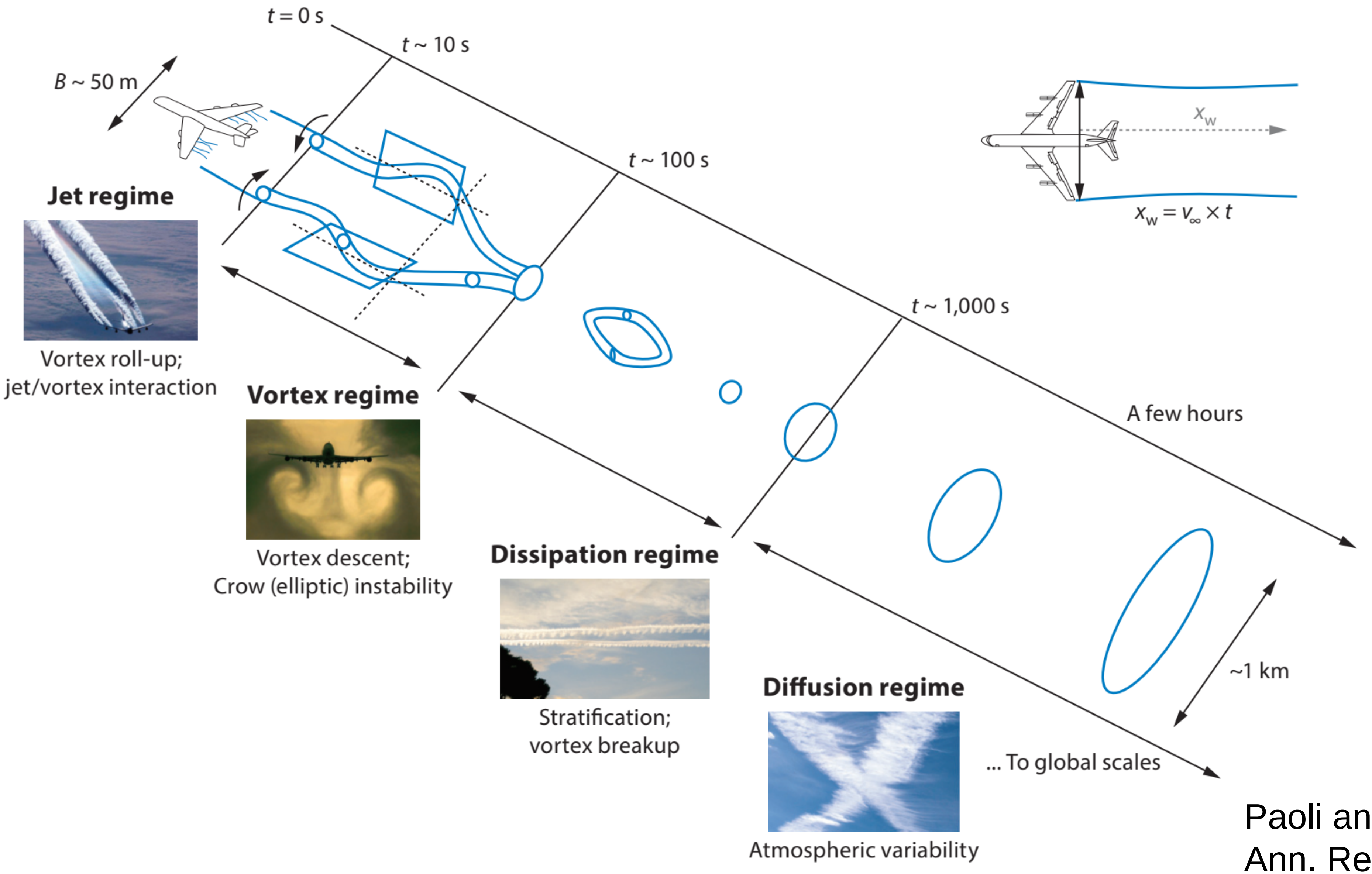
Modern jet engines have colder exhaust. Thus they can form contrails in warmer air, i.e. at lower altitudes.

Schumann et al., 2000

Is contrail formation possible only in high altitudes?

Formation of a contrail at start in very cold air: T=–45°C
https://www.reddit.com/r/aviation/comments/ugtymq/when_you_hit_the_chemtrail_switch_too_early_by/

Temporal evolution and phases of contrails

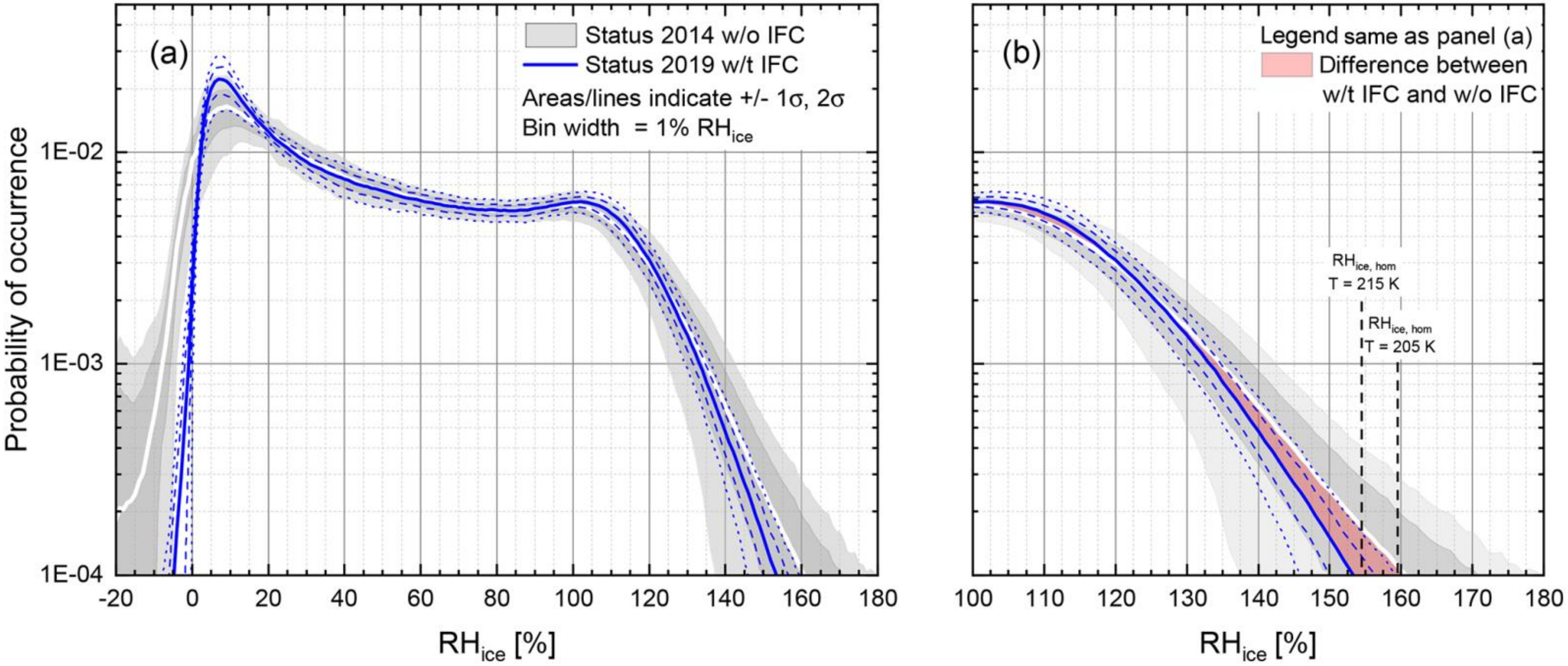


Paoli and Shariff,
Ann. Rev. Fluid Mech. 2016

persistent (i.e. long-lived) contrails: Ice supersaturated regions (ISSR)

- only persistent contrails have a non-negligible climate effect
- persistence requires ice supersaturation (RHi ≥ 100%)
- ISSRs occur mostly 0-200 hPa beneath the tropopause
- roughly 10 to 15% of all flight distances transsect ISSRs

Photo: N. Dotzek

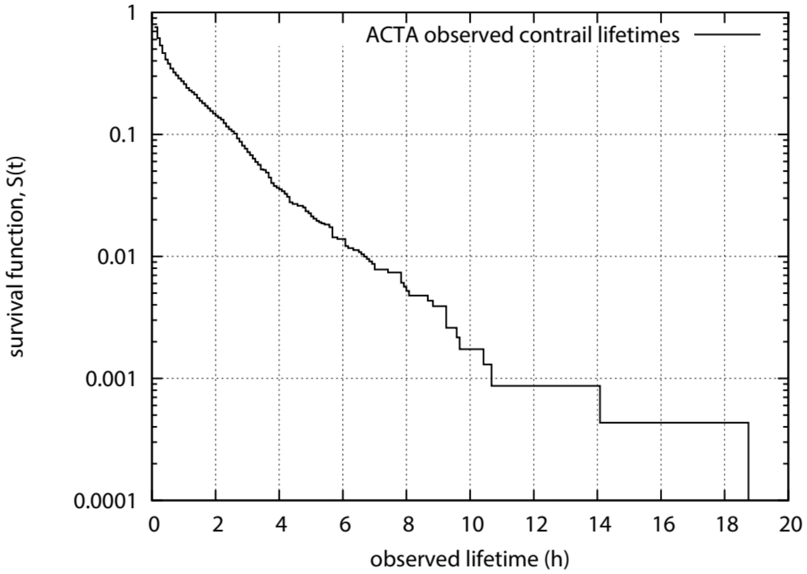


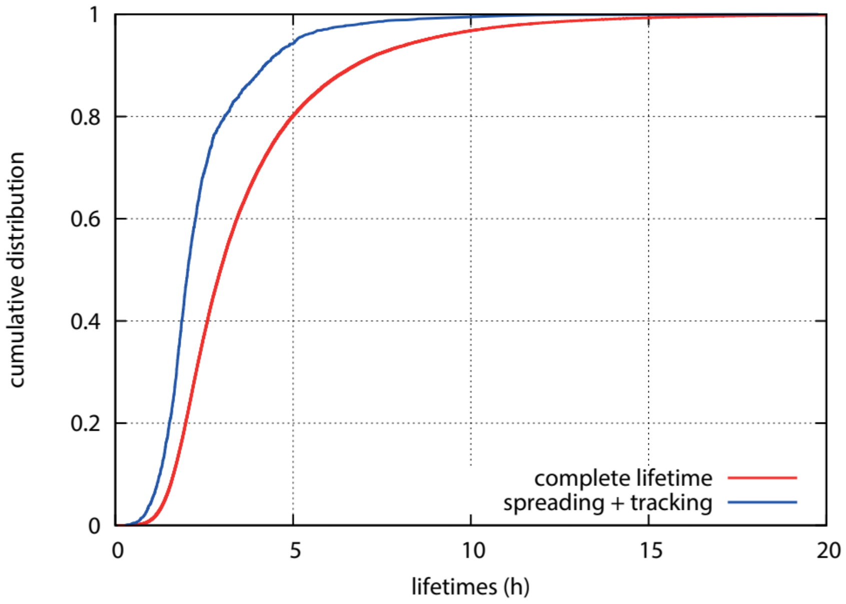
MOZAIC data 1995-2010
Petzold et al. 2021

„lifetimes“ of contrails

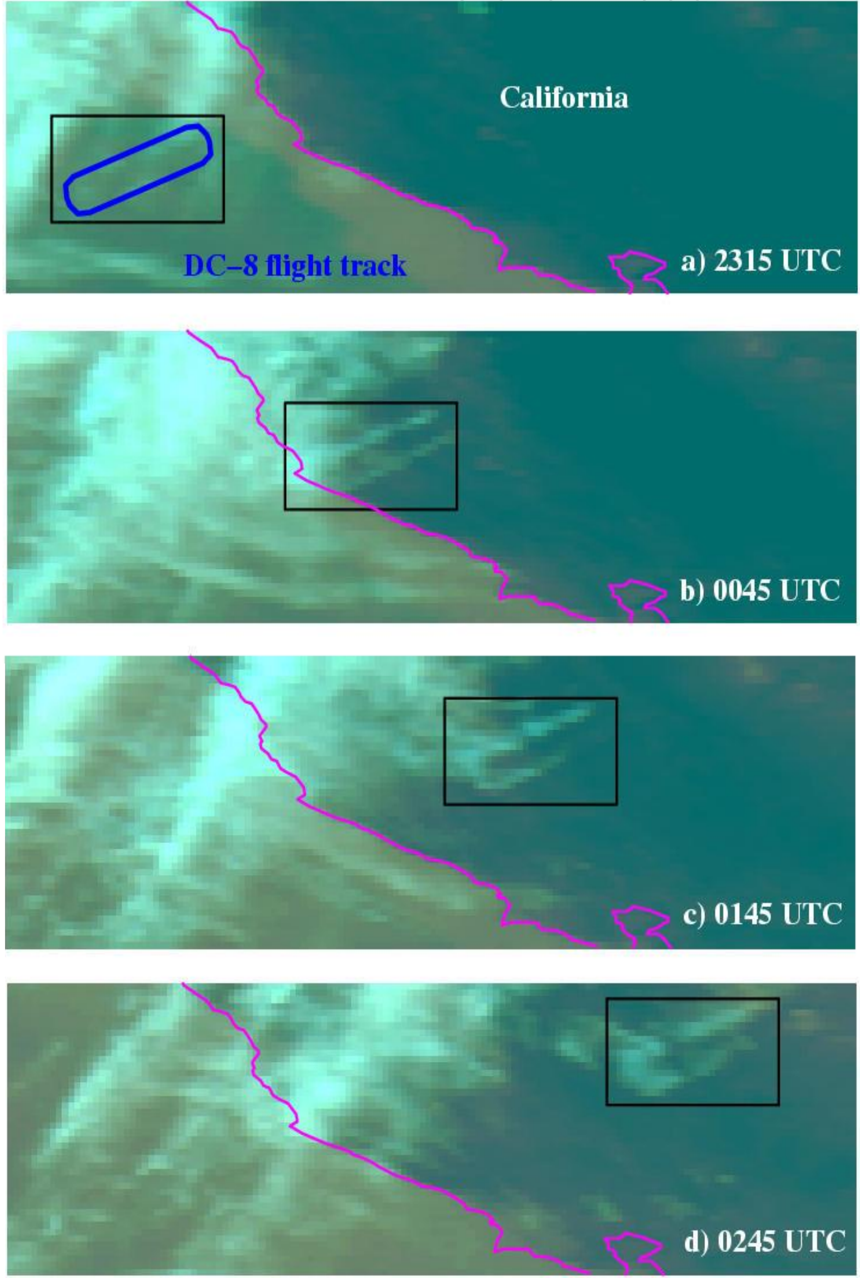
- most contrails are short (RHi<100%, duration less than 5 minutes)
- 10-15% of all contrails are persistent
- typical duration 2-3h, but >17 h have been observed
- contrail termination due to subsidence, sedimentation of crystals, and mixing with natural cirrus.

Gierens & Vazquez-Navarro, 2018





Minnis et al. 1999

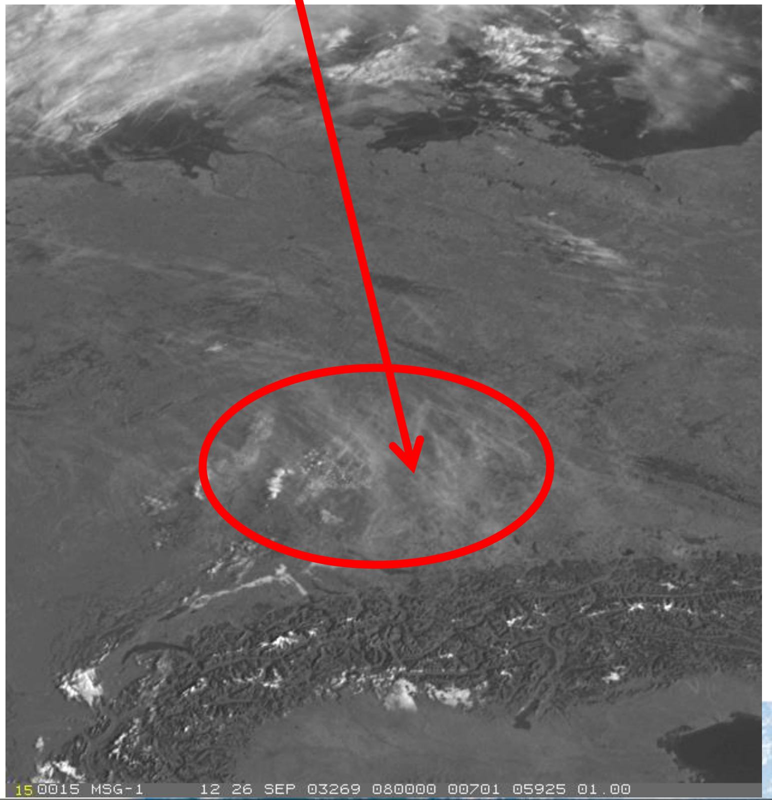


Interaction of radiation with contrails: longwave and shortwave contrasts

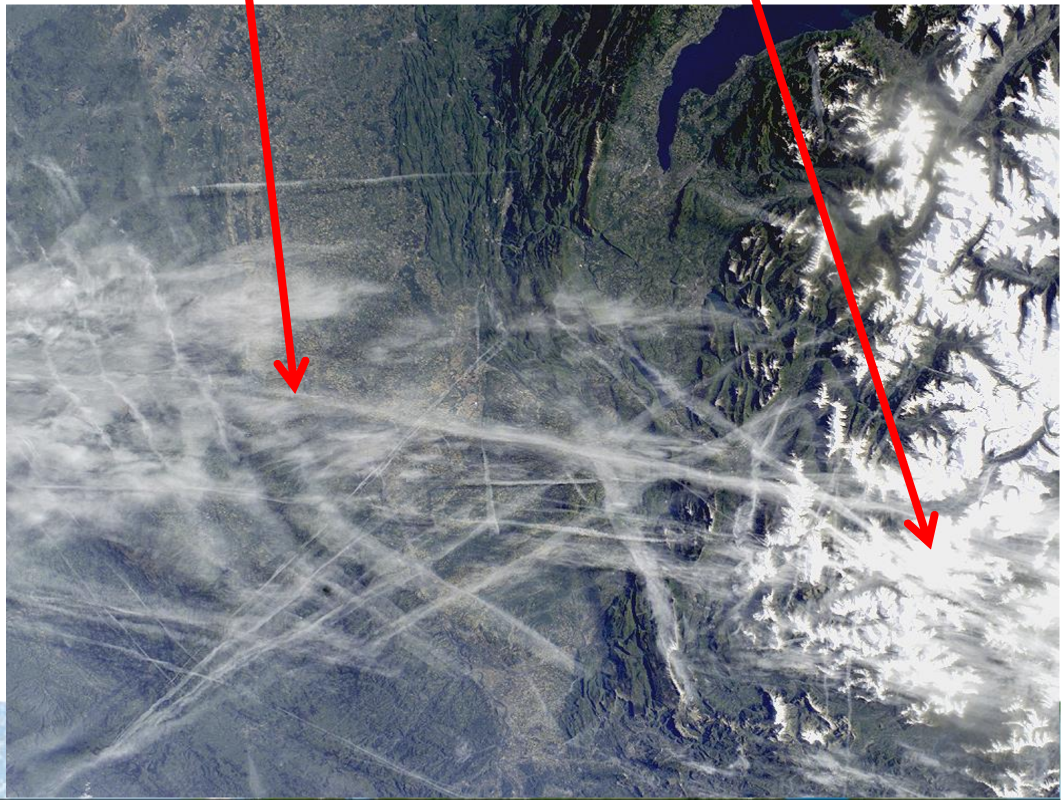
Influences by:
Temperature of the contrail
ground temperatur
position of the sun
background albedo
crystal habits and –sizes

Cold contrail over a warm background: strong warming

Thick (white) contrail over a dark background: strong cooling



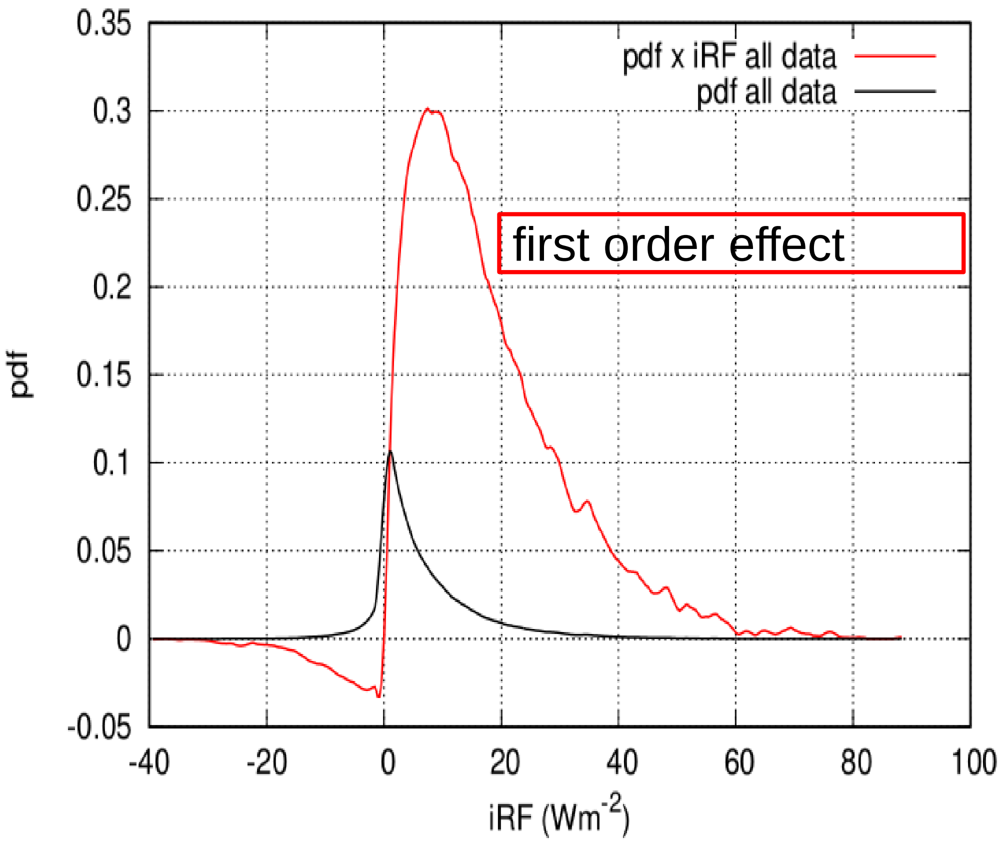
LW contrast: heating



SW contrast: cooling

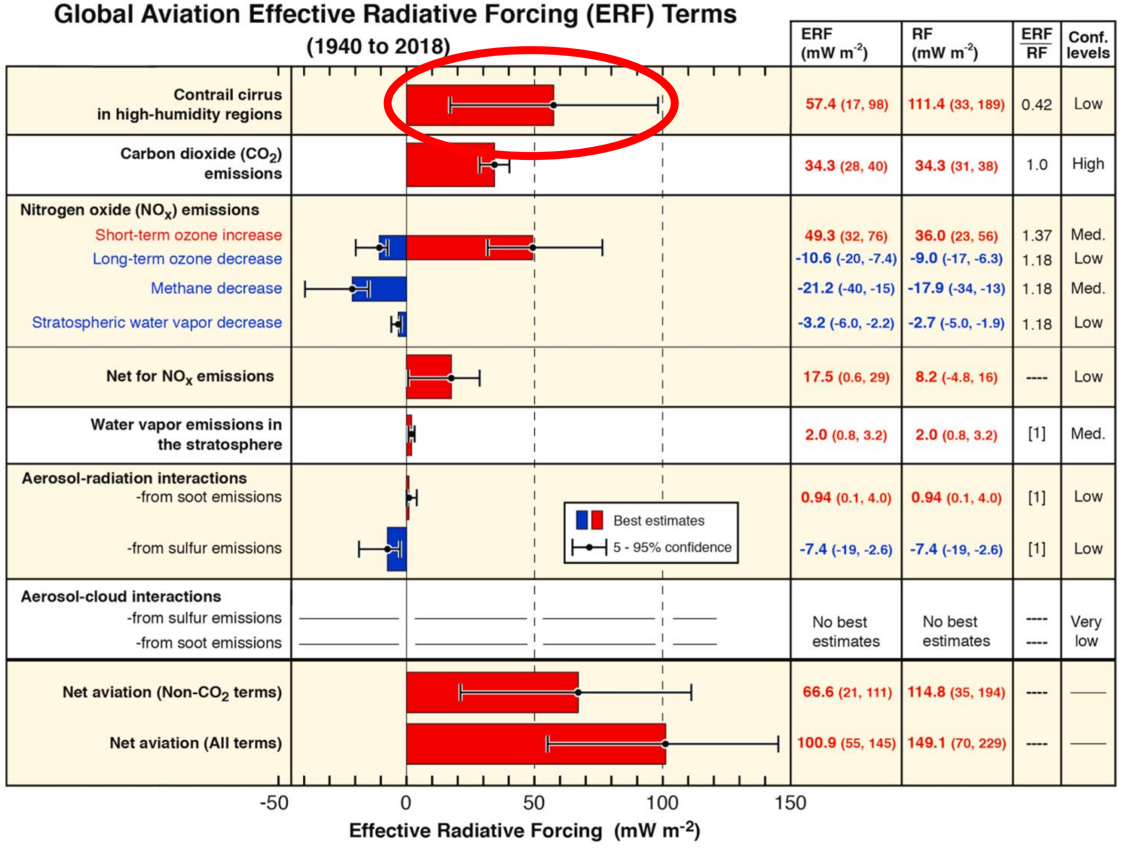
no SW contrast

Radiative effect of single contrails and effective radiative forcing on climate



first order effect

Wilhelm et al., 2021



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	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)	----	——

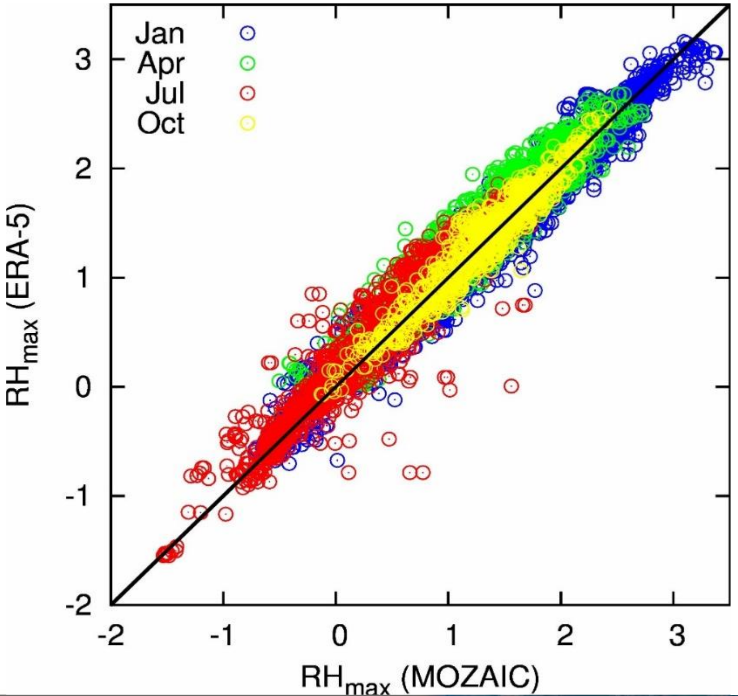
Lee et al. 2021

Avoidance of persistent contrails ⇔ Don‘t fly in ISSRs

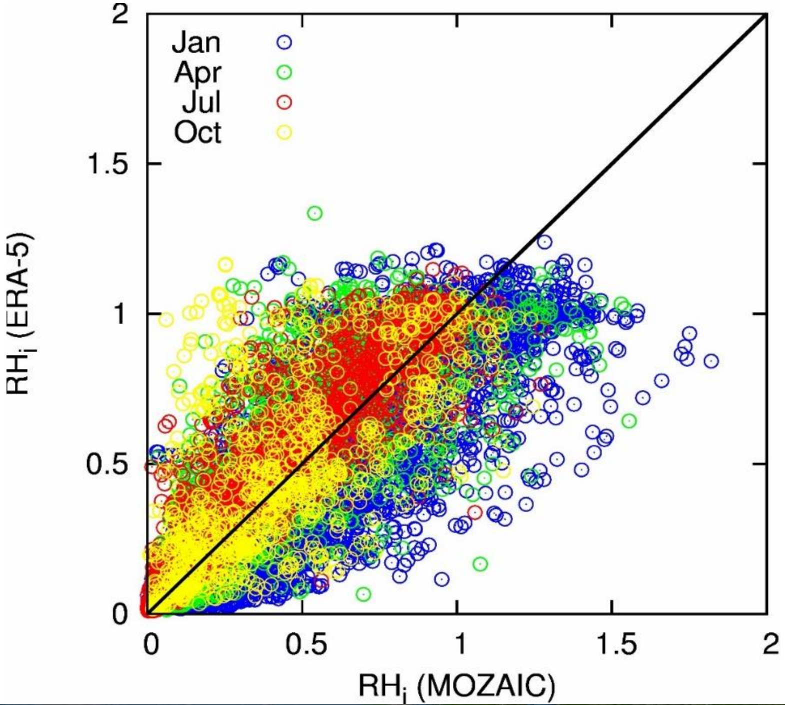
- Three steps with increasing difficulty:

1. Predict the **formation** of contrails ⇨ Schmidt-Appleman criterion
2. Predict the **persistence** of contrails ⇨ Forecast of ice supersaturation
3. Predict the individual **radiative impact** of a contrail expressed in an appropriate metric (EF, GWP, ATR, ...)

Schmidt-Appleman criterion (RH_{max}>1)



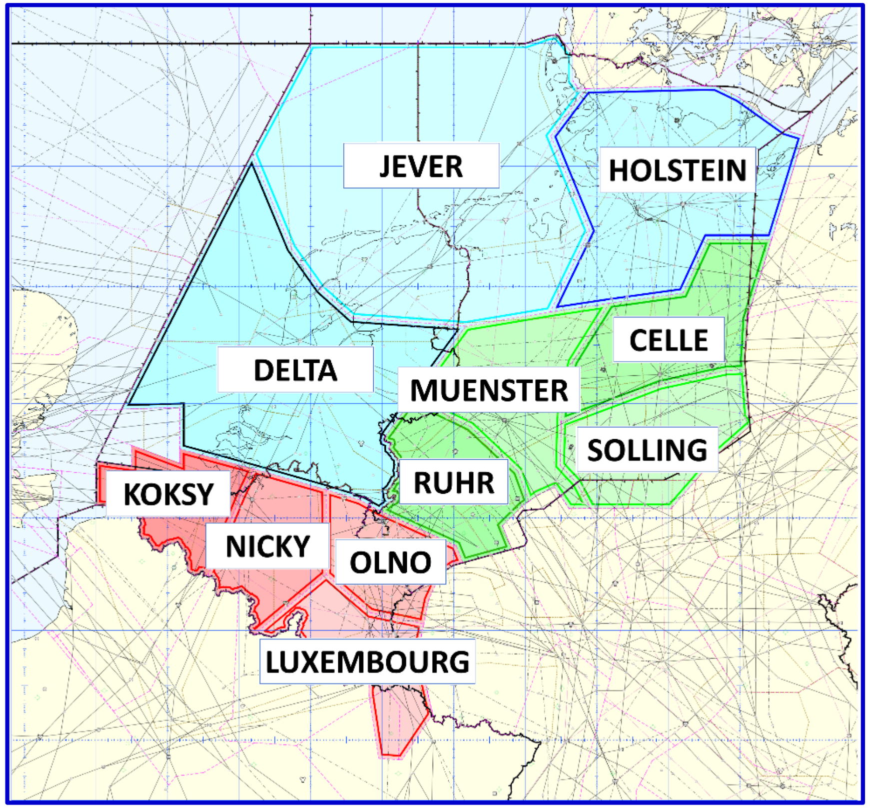
Contrail persistence criterion (RH_i>1)



Gierens et al. 2020

The DLR-MUAC experiment for tactical avoidance of contrails

- 1 February – 22 October 2021, daily 1600-2200 UTC
- Flight levels 240 – 400 (hft)
- ICON-EU forecast of temperature and relative humidity
- Avoidance (tactical measures) each even day, if possible
- Validation using contrail detection in MSG satellite data



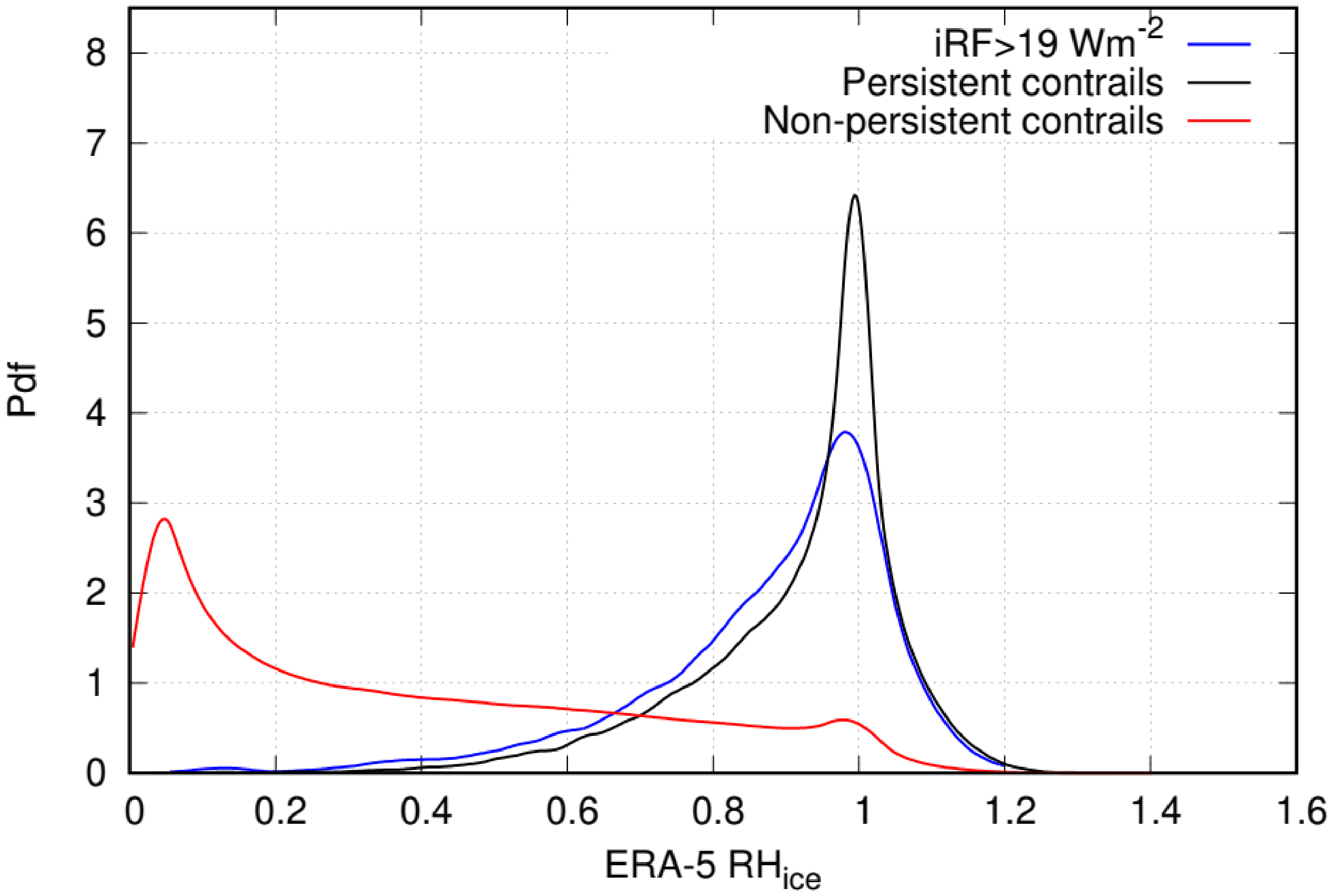
cases		985	23
		no action	**aircraft deviated**
persistent contrails observed	**yes**	44.9 ***a***	21.7 ***a’***
	no	55.1 ***c***	78.3 ***c’***

- We could demonstrate that ***a/c>a‘/c‘***, and that this does very probably not due to random fluctuations.
- It is thus possible to avoid persistent contrail in daily operations with takctical measures.
- However, the unaffected yes/no ratio ***a/c=44.9/55.1*** shows that forecast of ISSR is almost like tossing a coin.

Conditional distributions of RHi

Wilhelm, Gierens, and Rohs, 2021:
Analysis of 10 years of IAGOS data

Many quite dry cases in ERA-5 where IAGOS measurements show ice supersaturation and SAC fulfilled

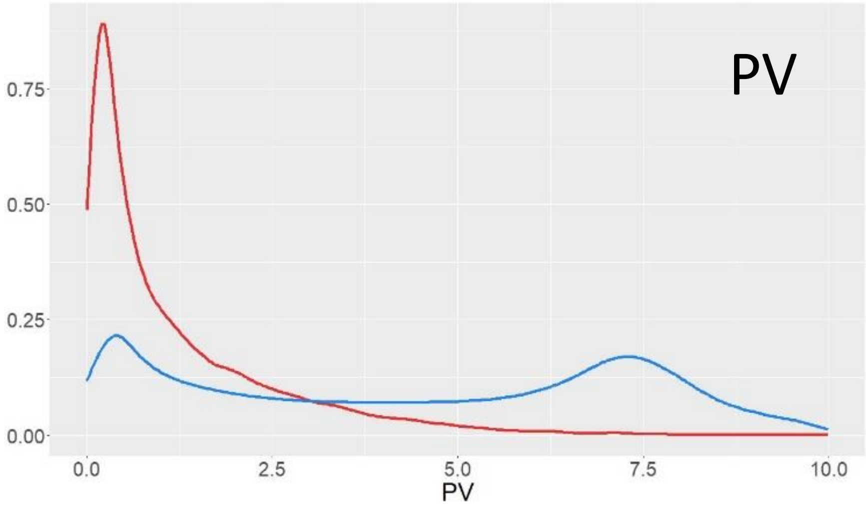


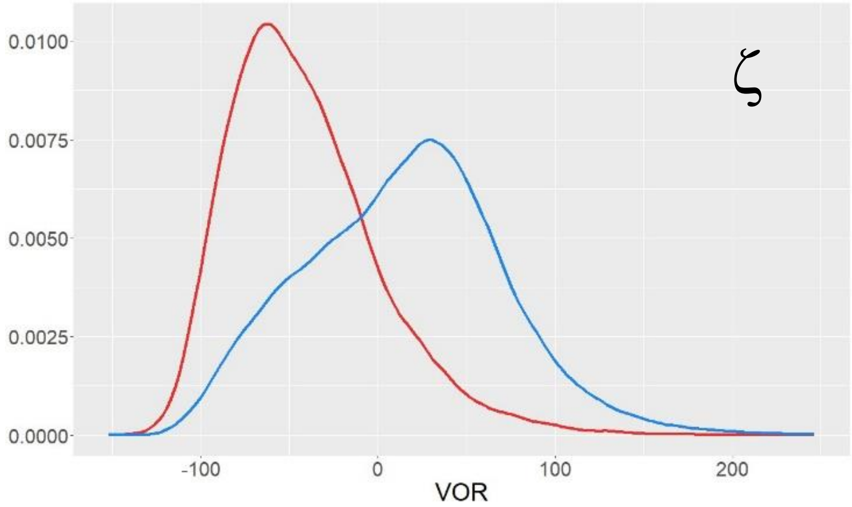
Red: No contrails or at least no persistence possible (acc. to IAGOS data)

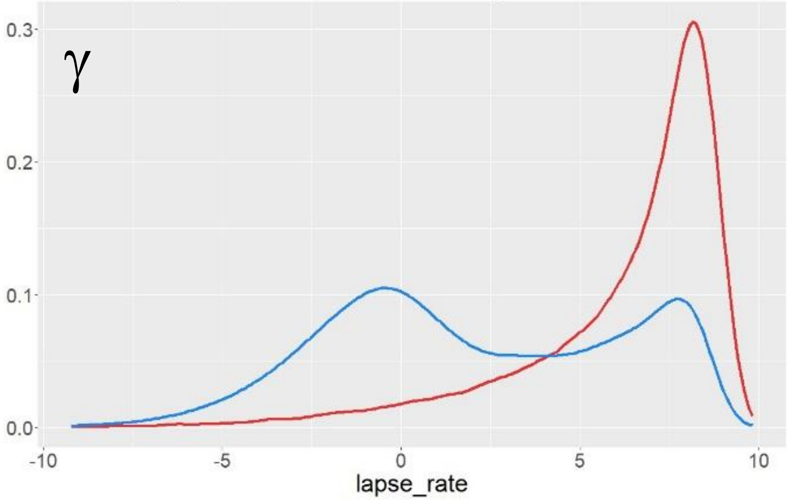
Black: Persistent contrails possible (acc. to IAGOS data)

Blue: Persistent contrails with strong instantaneous RF possible (acc. to IAGOS)

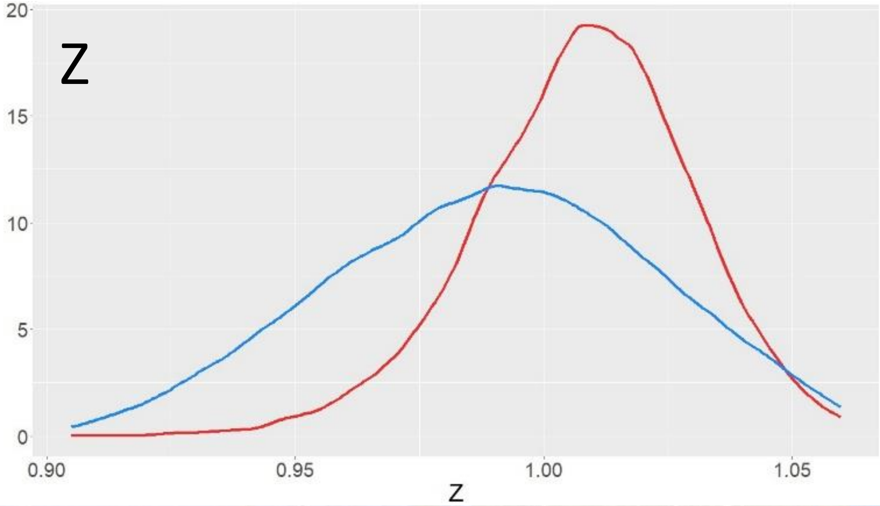
Dynamical proxies: Relation between ISS and PV, ζ, γ, Z
Distinct conditional distributions







red: ISS,
blue: no ISS

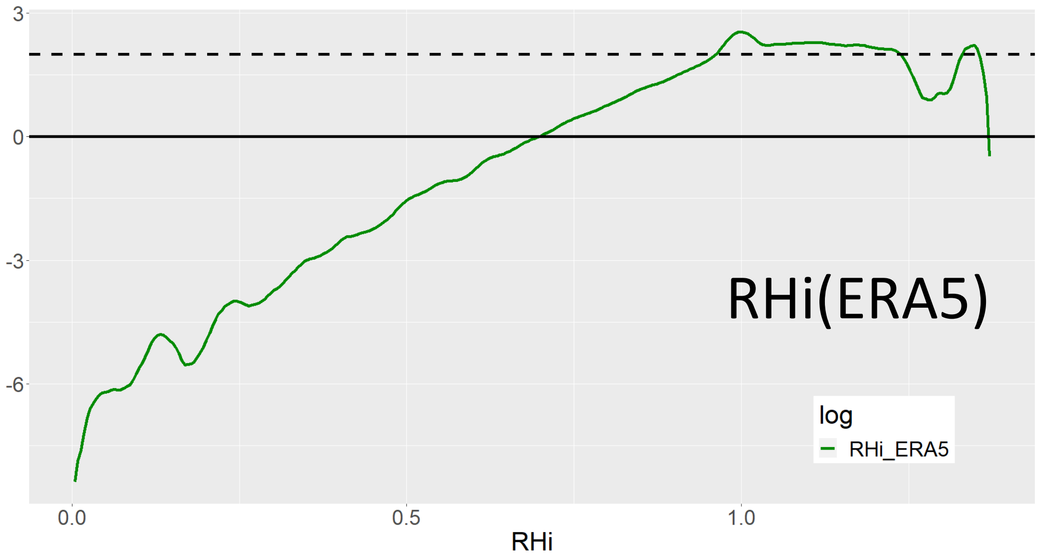


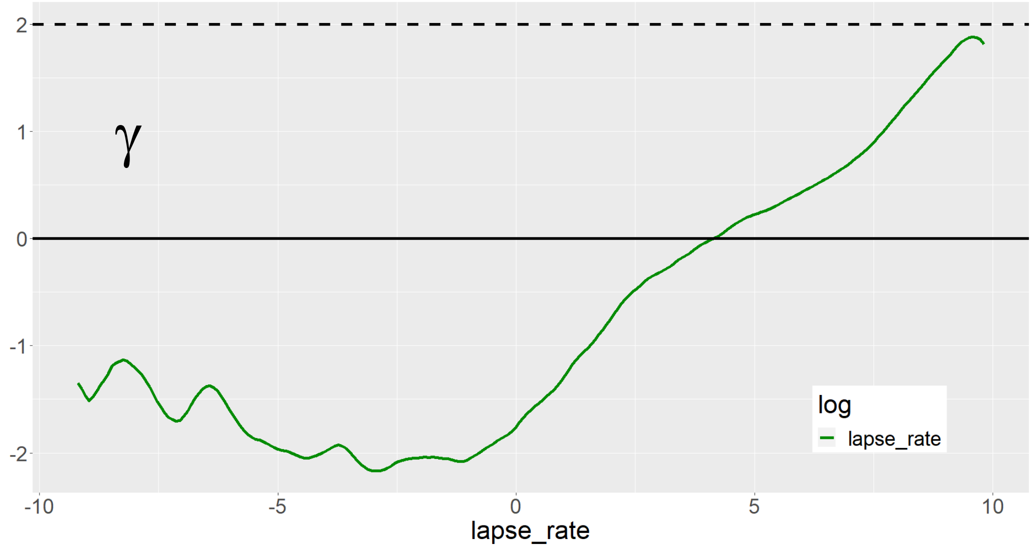
Log-likelihood ratios are too small!

- Use dynamical proxies in a Bayesian learning procedure:
- $\log(\Omega|x) = \log\Lambda + \log\Pi$
- with
- $(\Omega|x) = P(ISS|x)/P(\overline{ISS}|x)$
- $\Lambda = f_X(x|ISS)/f_X(x|\overline{ISS})$
- $\Pi = P(ISS)/P(\overline{ISS}), \log\Pi \approx -2$

- Unfortunately too small log-likelihood ratios (almost always < 2).
- Thus the probability for ISS does hardly raise above 1/2.

- Hofer et al., 2024, egusphere-2024-385





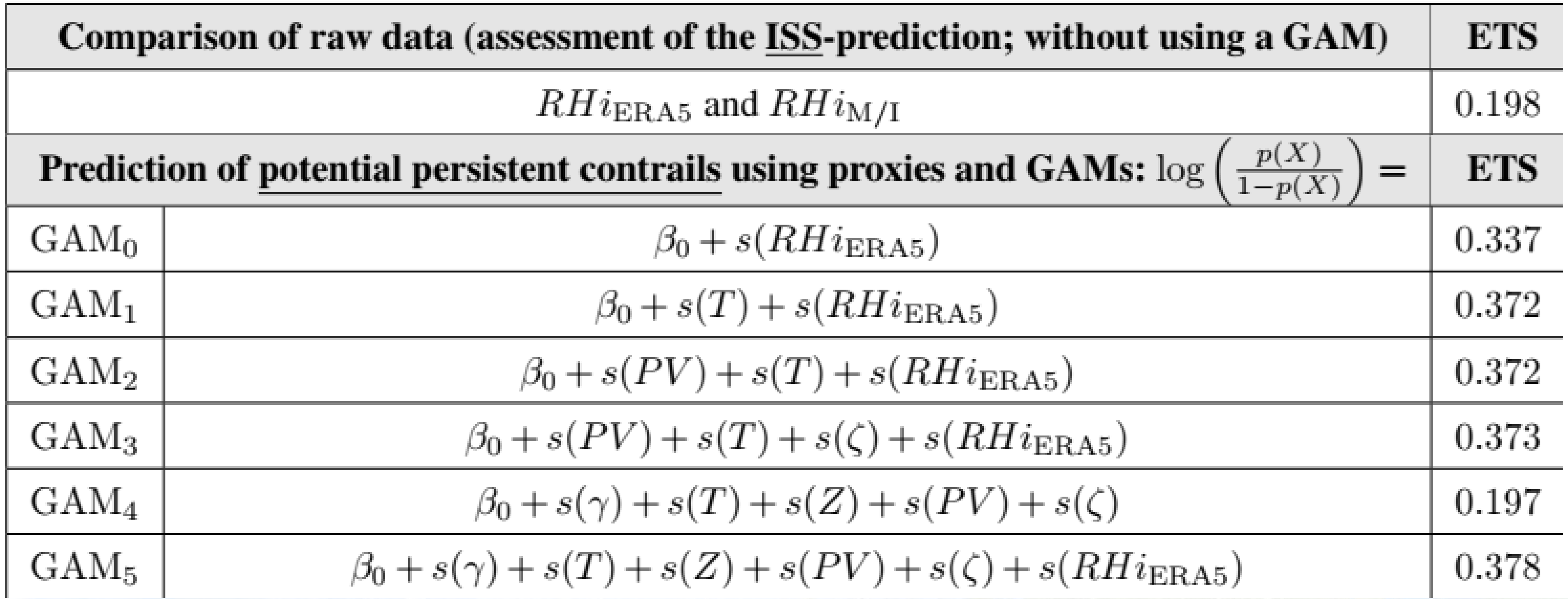
Regressions using dynamical proxies

Expectation of the absolute logit
Mutual information with RHi (IAGOS)

	RHi_{ERA}	T	ω	DIV	ζ	PV	γ	Z
E_{AL}	2.58	0.36	0.50	0.38	1.08	1.49	1.10	0.70
$I(RHi_{M/I}; X)$	1.26	0.29	0.06	0.04	0.37	0.57	0.38	0.23

Generalised Additive Model: $\log(\Omega|X) = \beta_0 + s_1(X_1) + s_2(X_2) + \ldots + s_p(X_p)$

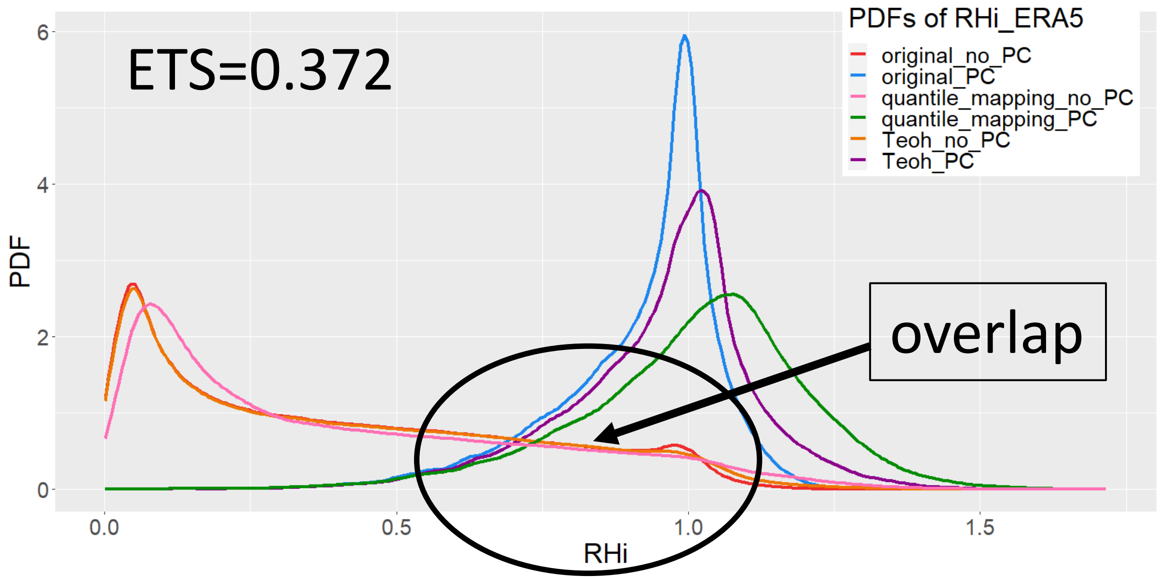
Hofer et al., 2024, egusphere-2024-385



Comparison of raw data (assessment of the ISS-prediction; without using a GAM)		**ETS**
RHi_{ERA5} and $RHi_{\mathrm{M/I}}$		0.198
Prediction of potential persistent contrails using proxies and GAMs: $\log\left(\frac{p(X)}{1-p(X)}\right) =$		**ETS**
GAM_0	$\beta_0 + s(RHi_{\mathrm{ERA5}})$	0.337
GAM_1	$\beta_0 + s(T) + s(RHi_{\mathrm{ERA5}})$	0.372
GAM_2	$\beta_0 + s(PV) + s(T) + s(RHi_{\mathrm{ERA5}})$	0.372
GAM_3	$\beta_0 + s(PV) + s(T) + s(\zeta) + s(RHi_{\mathrm{ERA5}})$	0.373
GAM_4	$\beta_0 + s(\gamma) + s(T) + s(Z) + s(PV) + s(\zeta)$	0.197
GAM_5	$\beta_0 + s(\gamma) + s(T) + s(Z) + s(PV) + s(\zeta) + s(RHi_{\mathrm{ERA5}})$	0.378

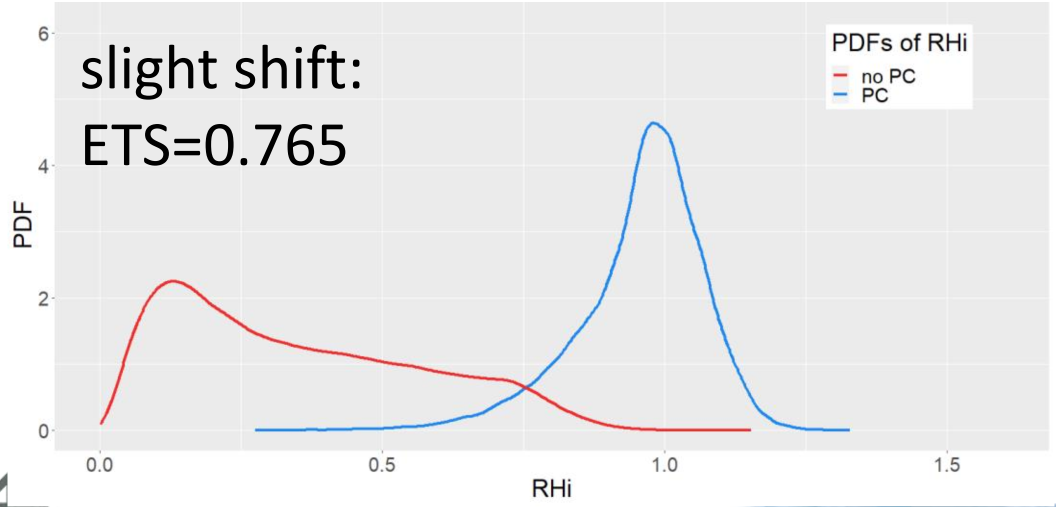
Main problem: large overlap between conditional RHi distributions

- inclusion of RHi(ERA5) is essential for GAMs
- ETS values do not get larger than about 0.38
- inclusion of proxies does not raise ETS significantly
- a priori correction of RHi does not help
- better results are prohibited by the large overlap btw. the cond. pdfs
- reducing the overlap would yield much better results



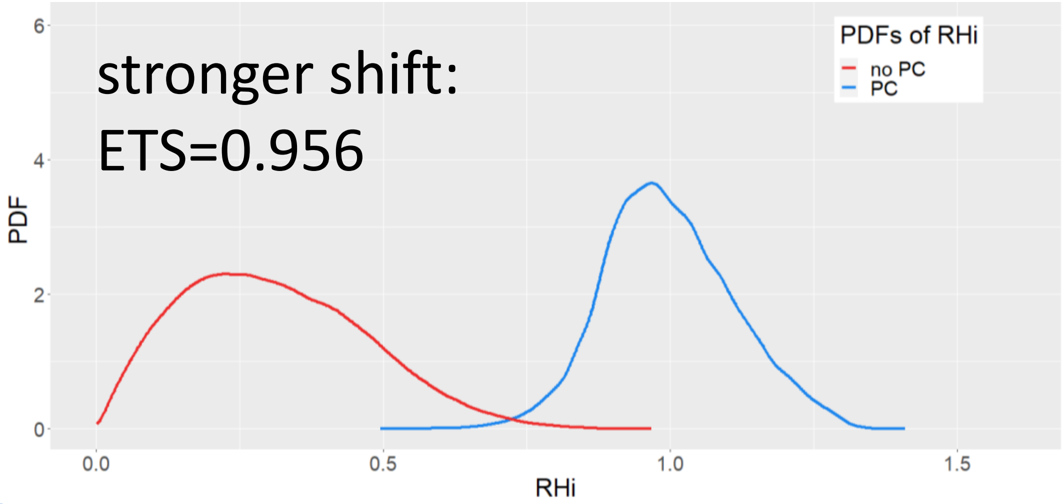
ETS=0.372

overlap



slight shift:

ETS=0.765



stronger shift:

ETS=0.956

Hofer et al., 2024, egusphere-2024-385

Necessary further steps

- Improve the forecast of RH and ISS in the upper troposphere:
    - Regular measurements of humidity on cruise levels with instruments aboard passenger and cargo aircraft (like AMDAR, but with much more aircraft and availability of data in cruise)
    - Assimilation of data of upper-tropospheric relative humidity into numerical weather forecast
    - Improved representation of the interaction of cirrus clouds and their humid environment in numerical weather forecast models

- Improved methods for the identification of contrails in satellite imagery for validation purposes

- Improvement of operational measures:
    - Automatic strategic and tactical flight guidance for contrail avoidance
    - ATCO position with automated advisory for ISSR prevention

- Including all non-CO2 effects, CO2 emissions and operational cost in a scheme for minimising climate impact of aviation (⇒ eco-efficient flight trajectories)

Thank you for your attention!

Photo: Ron Smith, Henstridge in Somerset UK