



Photo by A.Petzold

Long-lived contrails in cirrus clouds underestimated with uncertain climate impact

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Long-lived contrail-cirrus inside natural cirrus – What's the issue?

Linear contrail in clear sky

⇒ no significant radiative effect

Long-living contrail

⇒ evolution into contrail-cirrus
embedded in subvisible clouds

⇒ strong contrast to sky
without contrail

⇒ significant warming



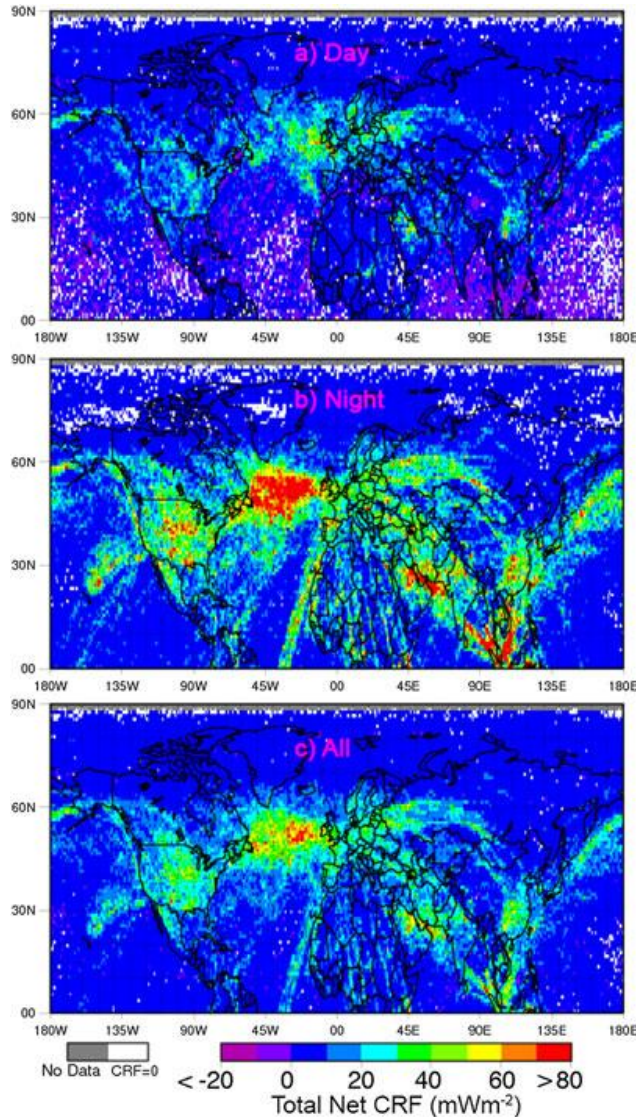
Contrail-cirrus in
cloudy sky

⇒ cloud optical depth
determined by cirrus

⇒ low contrast to sky
without contrail-cirrus

⇒ minor warming

The unknown impact of contrails in clouds – Radiative forcing

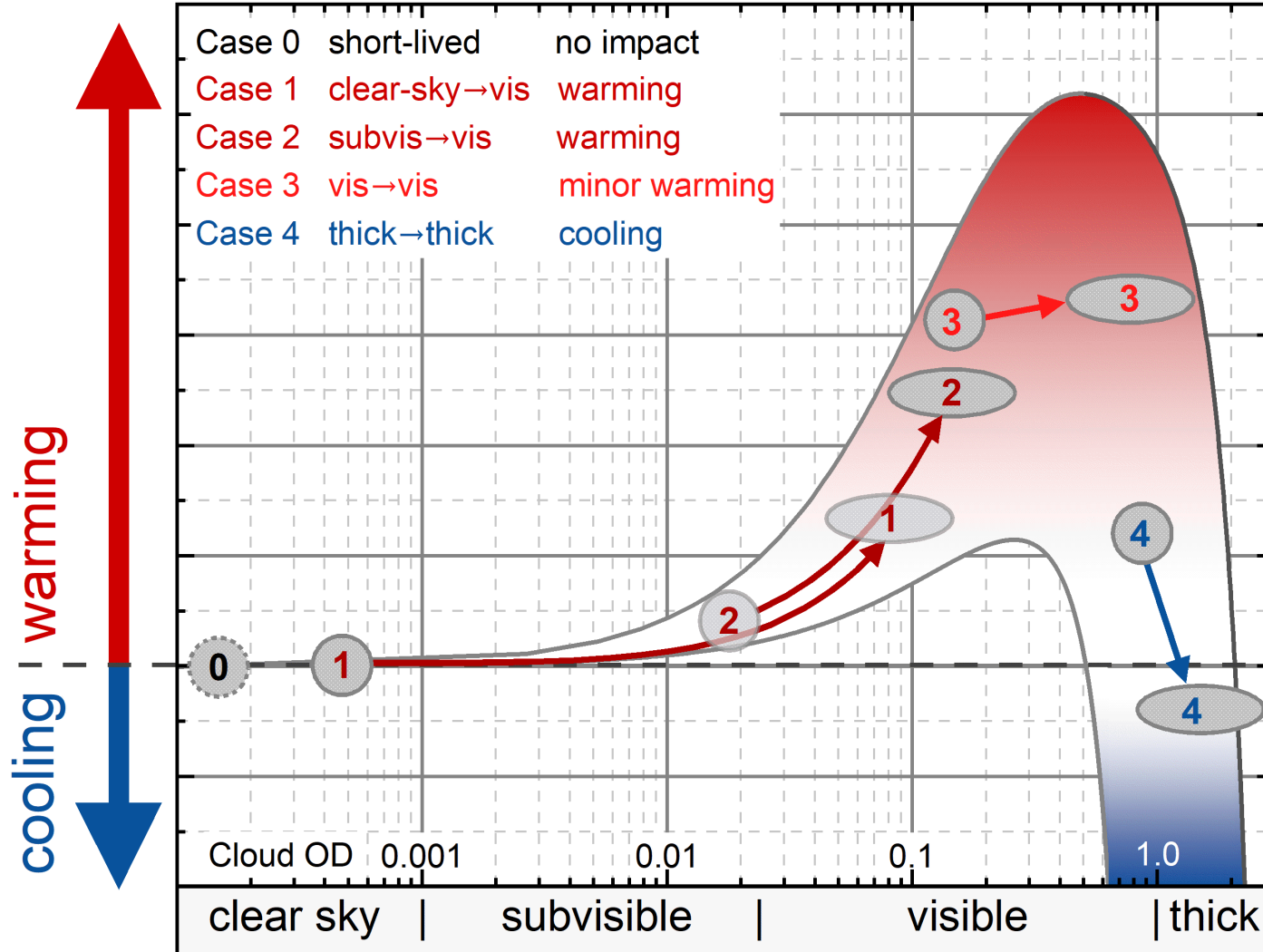


Normalized Contrail Radiative Forcing (CRF)
over Different Background Types from NH Aqua MODIS Data 2006
Spangenberg et al., GRL 2013

	Ice cloud	Clear sky
Day		
Shortwave CRF (Wm^{-2})	10.4	14.6
Longwave CRF (Wm^{-2})	11.7	18.5
Net CRF (Wm^{-2})	1.3	3.9
Night		
LCRF/NCRF (Wm^{-2})	11.0	16.9

⇒ **Contrail radiative forcing over ice clouds is significantly reduced compared to clear sky**

The unknown impact of contrails in clouds – Climate impact



- Case 0 no resulting climate impact
no climate impact
- Cases 1 and 2 contrail-cirrus net warming
net warming climate impact
- Cases 3 and 4 minor warming or cooling, depending on cirrus OD
ambiguous climate impact

... but detailed radiative transfer calculations are missing ...

Petzold et al., Nat Commun 16, 9695, 2025

The unknown impact of contrails in clouds – Open questions

Which fraction of contrail-cirrus exists in

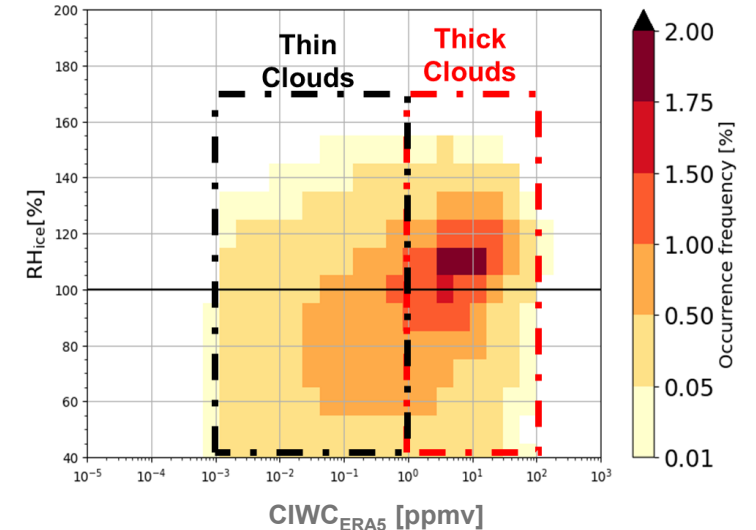
- clear sky and subvisible clouds, and
- visible to optically thick clouds ?

What is the radiative impact of contrail-cirrus embedded in pre-existing cirrus clouds ?

How do contrail-cirrus and natural cirrus interact?

In Service Aircraft for a Global Observing System

European Research Infrastructure for monitoring climate and air quality using commercial aircraft



IAGOS in a Nutshell

Collaborates with 8 airlines globally

Operates 10 aircraft equipped with IAGOS instruments for

greenhouse gases, reactive gases, water vapour, aerosol, and clouds

Open data provided since 1994

IAGOS Capacitive Hygrometer ICH

Established technique for radiosondes

In-flight intercomparison $\Rightarrow \pm 5\%$ RH

No sampling line and pumps required

Increased response time at $T < -40^\circ\text{C}$

No detection of dry air ($\text{RH}_{\text{ice}} < 10\%$)

ERA5 Cloud Ice Water Content (CIWC)

Interpolation to IAGOS flight routes

Cloud categorization by ERA5 CIWC

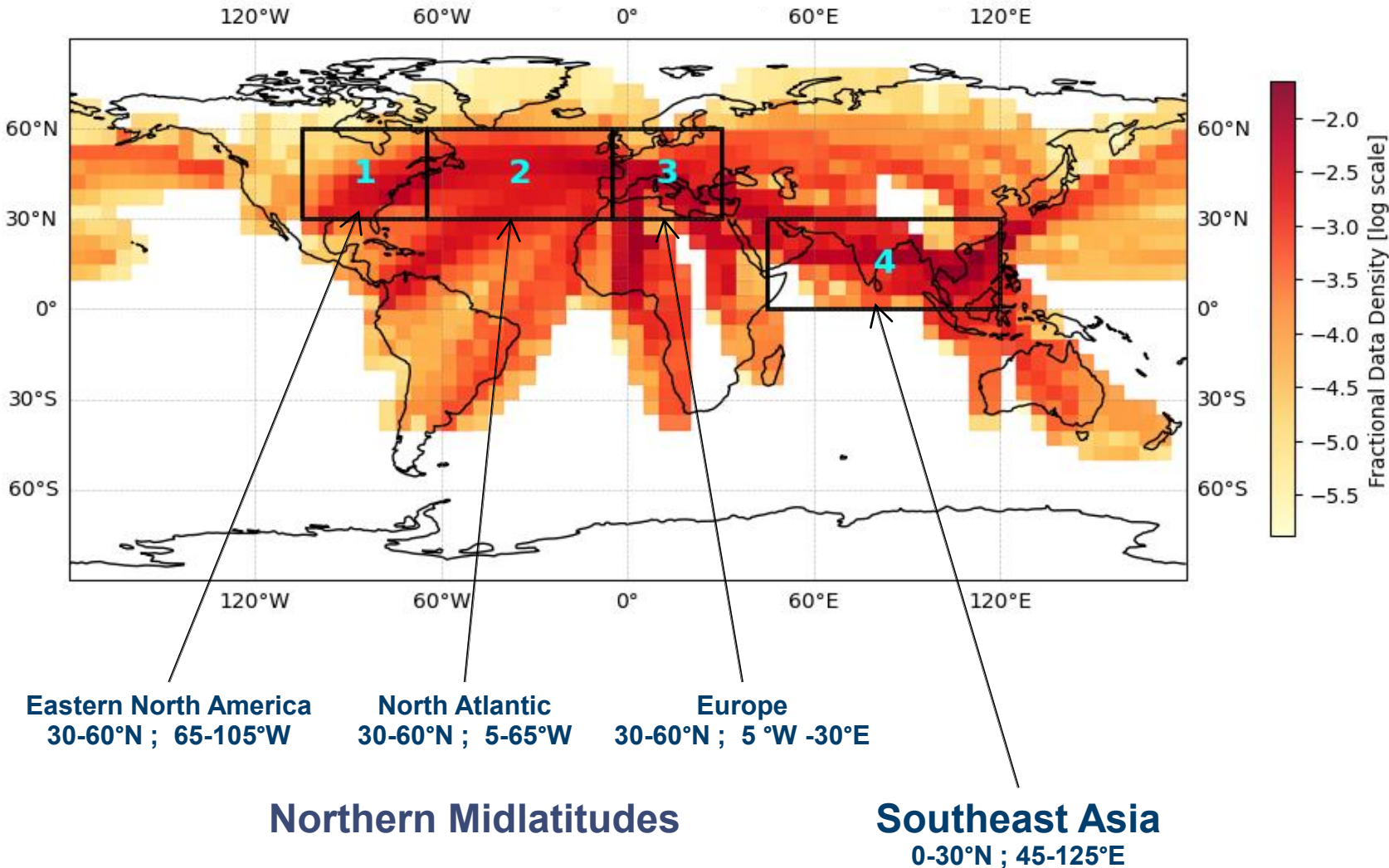
– *clear sky CIWC* < 0.001 ppmv

– *thin clouds*: CIWC < 1 ppmv

– *thick clouds*: CIWC ≥ 1 ppmv

IAGOS water vapour – cloud data coverage

Petzold et al., Nat Commun 16, 9695, 2025



Study period: 06/2014 – 12/2021

IAGOS spatial resolution of 1 km

$T_{\text{IAGOS}} \leq 235 \text{ K}$ to exclude liquid clouds

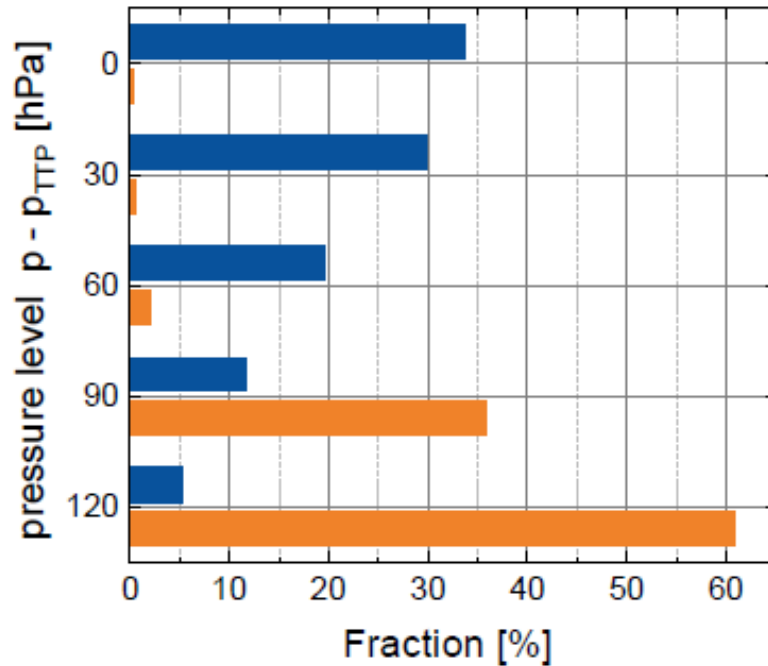
$p_{\text{IAGOS}} \leq 350 \text{ hPa}$, $> \sim 8.1 \text{ km}$ altitude

Relative humidity w.r.t. ice (RH_{ice})
 $> 20\%$ for cirrus cloud analysis and
to exclude dry stratospheric air mass

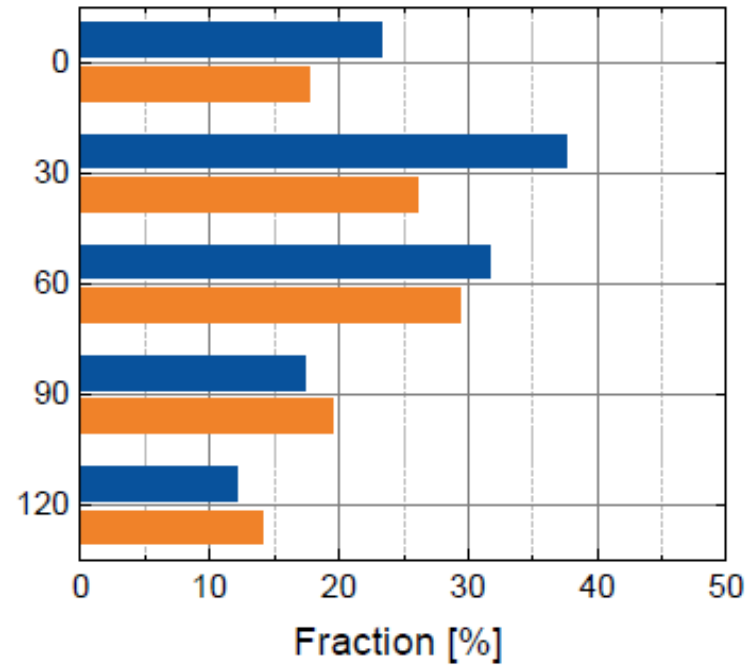
IAGOS water vapour – cloud data coverage

Petzold et al., Nat Commun 16, 9695, 2025

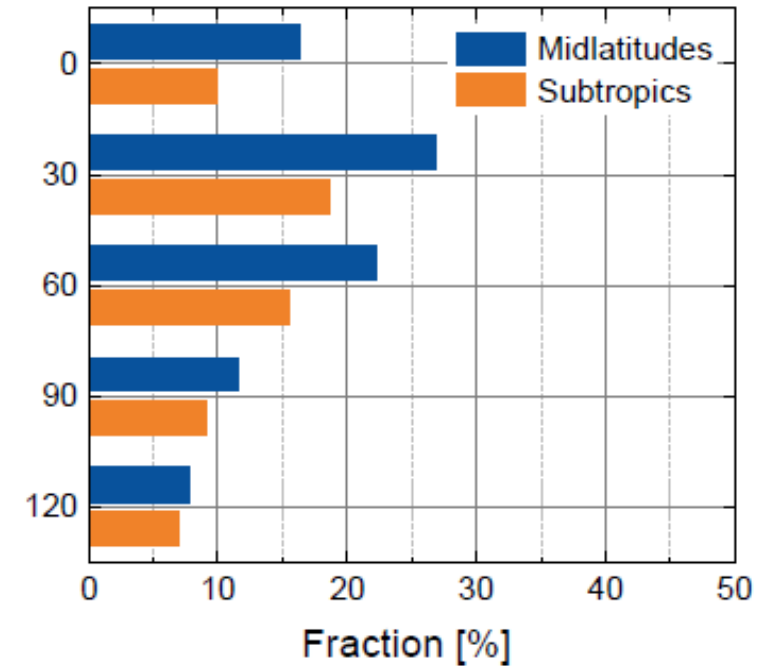
Distribution of data vs. flight levels



PCCR fraction per flight level



ISSR fraction per flight level

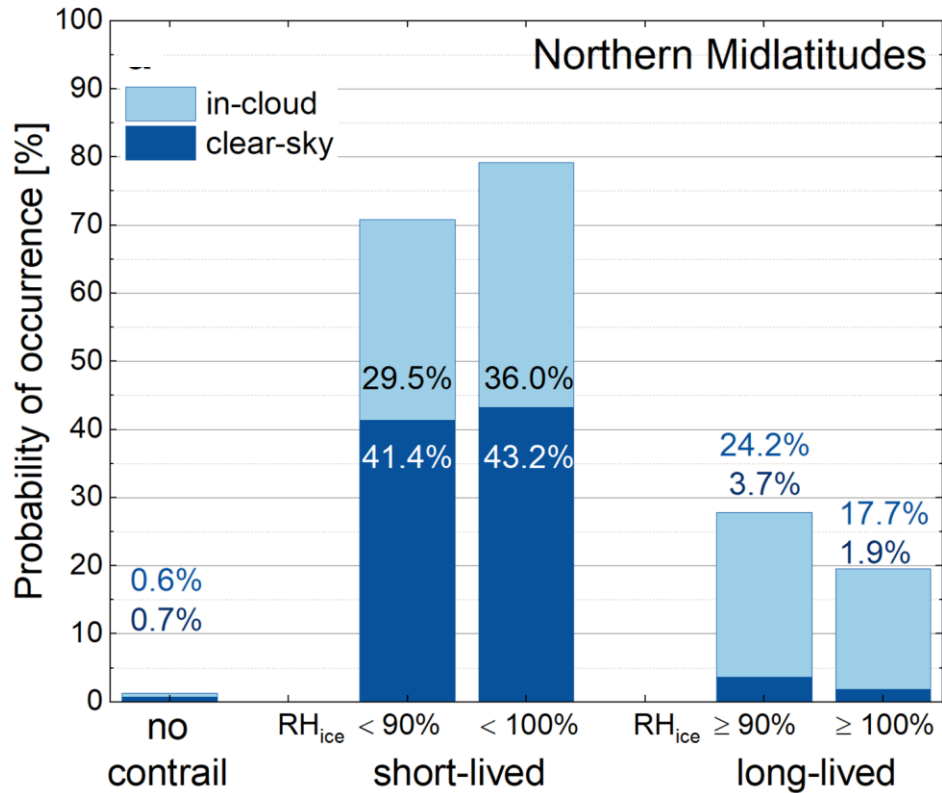


$RH_{ice} \geq 90\%$

$RH_{ice} \geq 100\%$

Occurrence of long-lived contrail-cirrus

Petzold et al., Nat Commun 16, 9695, 2025



Fraction of air masses promoting

- no contrail formation
(Schmidt-Appleman criterion SAC not fulfilled)
- formation of short-lived contrails
(SAC fulfilled, $RH_{ice} < \text{threshold } RH_{ice}$)
- long-lived contrails and contrail-cirrus
(SAC fulfilled, $RH_{ice} \geq \text{threshold } RH_{ice}$)

in-cloud ($CIWC_{ERA5} \geq 0.001$ ppmv)
clear-sky ($CIWC_{ERA5} < 0.001$ ppmv)

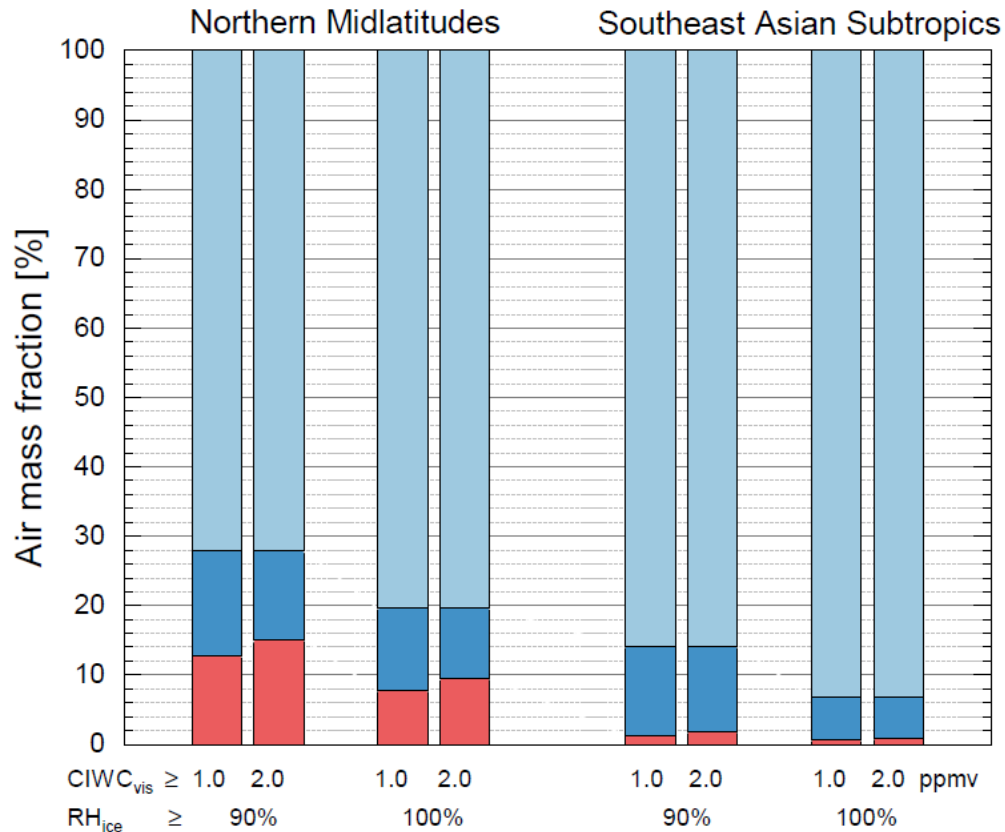
RH_{ice} : IAGOS
 CIWC : ERA5

Long-lived contrails

$RH_{ice} \geq 90\%$, SAC fulfilled clear sky 13% subvisible cirrus 41% visible cirrus 46%

Climate impact of long-lived contrail-cirrus

Petzold et al., Nat Commun 16, 9695, 2025



Fractions of air masses at Northern Midlatitudes with

no climate impact 70% - 80%
SAC not fulfilled
or short-lived contrails only

ambiguous climate impact 12% - 15%
contrail-cirrus in visible cirrus
with CIWC \geq 1.0 ppmv or 2.0 ppmv

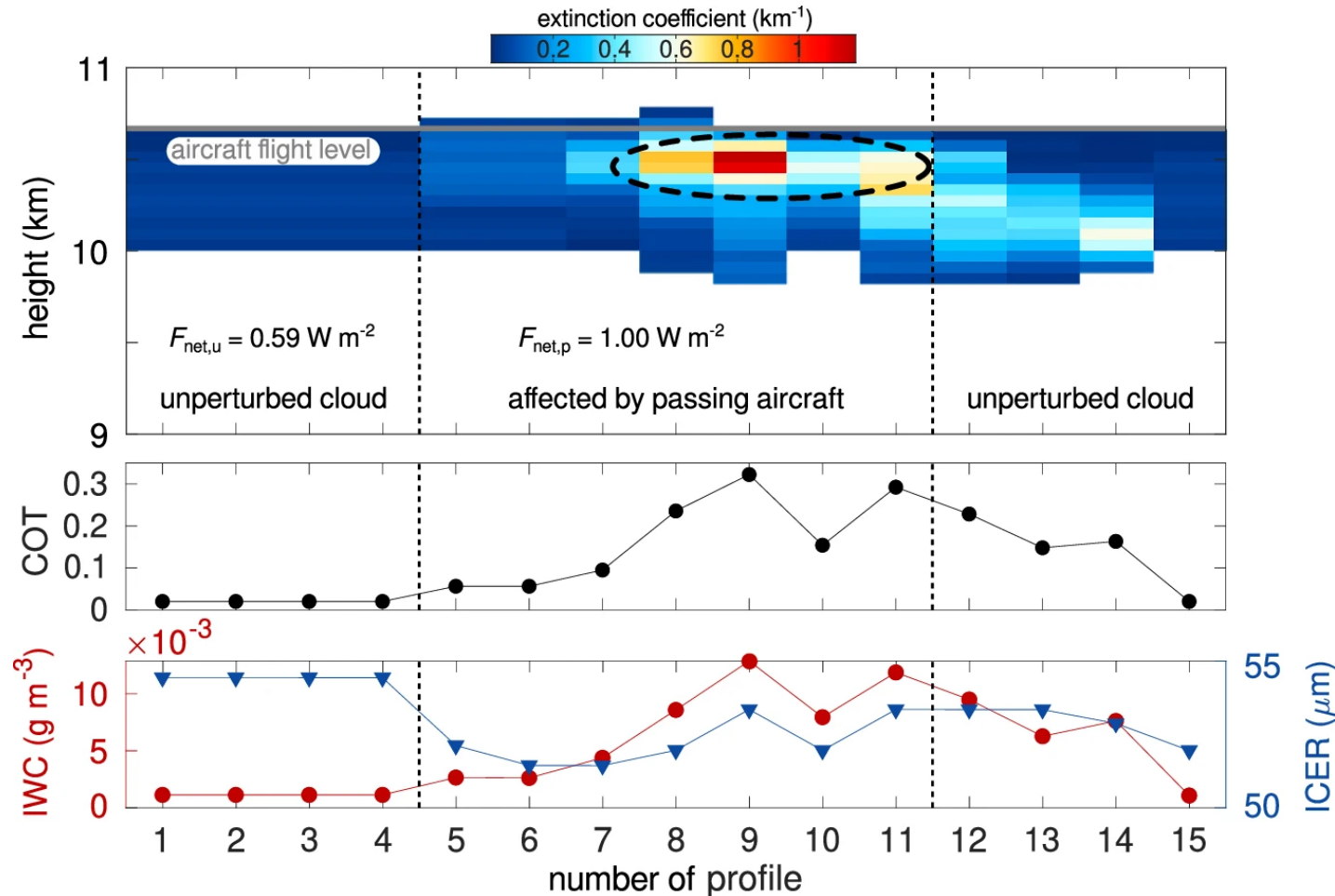
net warming climate impact 8% - 13%
contrail-cirrus in clear sky
or in subvisible cirrus

Contrail-cirrus climate impact

- no impact: no persistent contrails
- ambiguous: contrail-cirrus in visible cirrus
- warming: contrail-cirrus in clear sky or subvisible cirrus

Analysed pressure range: p_{TTP} - 15 hPa < p < 350 hPa

Long-lived contrail-cirrus inside natural cirrus – More new findings



Contrails inside cirrus increase

- net cloud radiative forcing (F_{net})
- cloud optical thickness (COT)
- cloud ice water content (IWC)
- cloud ice crystal number conc. (N_{ice})

Tesche et al., NatComm 2016

Seelig et al., Nat Comm 2025

Marjani et al., GRL 2022

Talk by Torsten Seelig
 Session AS 1.10, Room F2
 Wed, 06 May, 09:10–09:20

Analysis of CALIOP profiles: Seelig et al., Nat Commun 16, 10703, 2025

Long-lived contrail-cirrus inside natural cirrus – More new findings

Contrails formation and persistence inside cirrus

- modifies contrail formation by increasing water vapour via sublimated cirrus ice crystals in engine exhaust;
 - modifies cirrus microphysical and optical properties by increasing the cirrus ice crystal number
⇒ contrail-induced cirrus cloud perturbations;
 - affects the vertical distribution of cirrus by reducing sedimentation ⇒ fast cloud adjustment.
- Verma and Burkhardt, ACP 2022
Verma and Burkhardt, JGR 2026
 - Verma and Burkhardt, ACP 2022
Marjani et al., GRL 2022
Verma and Burkhardt, JGR 2026
 - Verma and Burkhardt, JGR 2026

More talks and posters on that topic

Session AS1.10 Mixed-phase and ice cloud observations and modelling

- Ed Gryspeerd**: Aircraft as a natural experiment on ice clouds TALK Wed, 06 May, 09:40–09:50 Room F2
- Jin Maruhashi**: Success and failure of contrail models TALK Wed, 06 May, 09:50–10:00 Room F2
- Mahshad Soleimanpour**: Observation of In-Cirrus Contrail Properties POSTER Tue, 05 May, 08:30–10:15 Hall X5 | X5.78
- Oliver Driver**: Transient contrails as an opportunity for UT humidity estimation POSTER Tue, 05 May, 08:30–10:15 Hall X5 | X5.78

CL3.1.5 Advances in understanding solar radiation modification technologies and their Impact on the Earth System

- Gavin Leong**: De-risking cirrus management TALK Thu, 07 May, 14:55–15:05 Room 0.31/32

AS3.31 Towards sustainable road traffic, shipping and aviation: from emissions to climate and air quality effects

- Part 1 of the session on aviation emissions and their climate effects TALKS Fri, 08 May, 08:30–10:15 Room 1.85/86

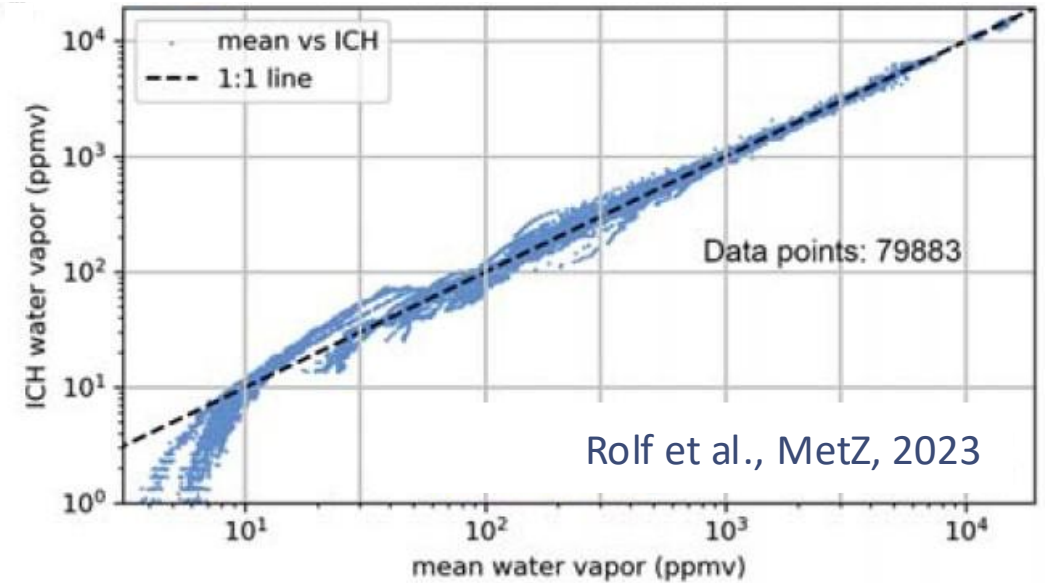


Thank you for your attention!
You find more on www.iagos.org

Acknowledgments:

We gratefully acknowledge the support by the airlines Lufthansa, Air France, China Airlines, Hawaiian Airlines, Air Canada, Iberia, Discover, Cathay Pacific carrying IAGOS instruments free of charge.

Supplement: IAGOS Humidity Observation System



IAGOS Capacitive Hygrometer ICH

- Established technique also for radiosondes
- In-flight intercomparison $\Rightarrow \pm 5\%$ RH
- Increased response time at low T ($< -40^\circ\text{C}$)
- **No sampling line and pumps required**
- **No detection of dry air ($\text{RH}_{\text{ice}} < 10\%$)**

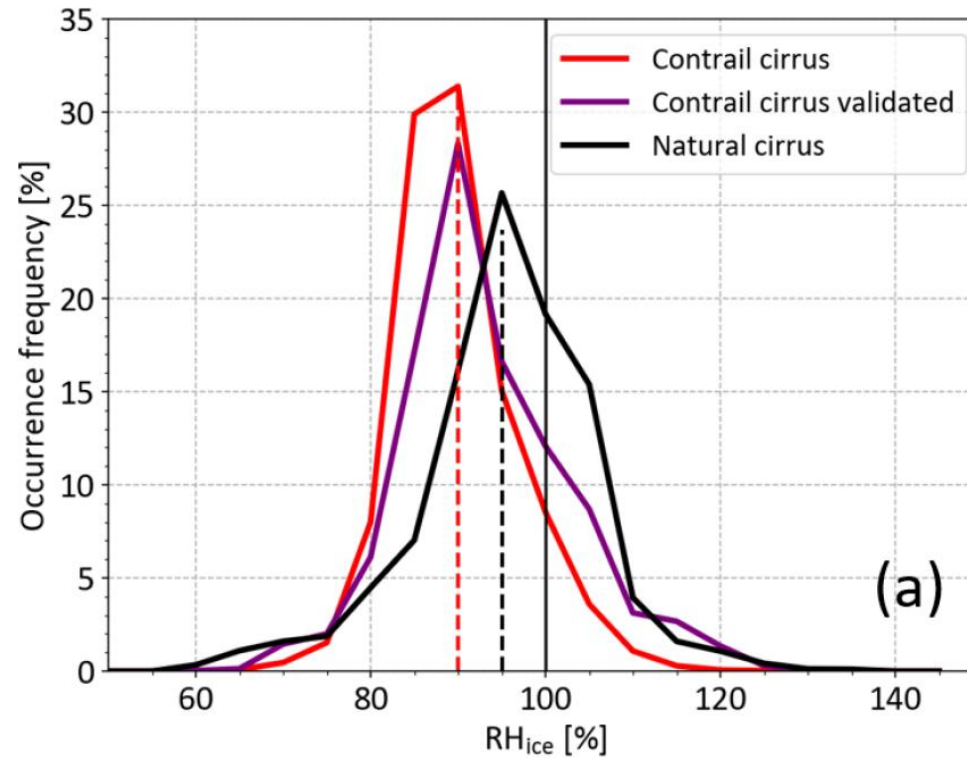
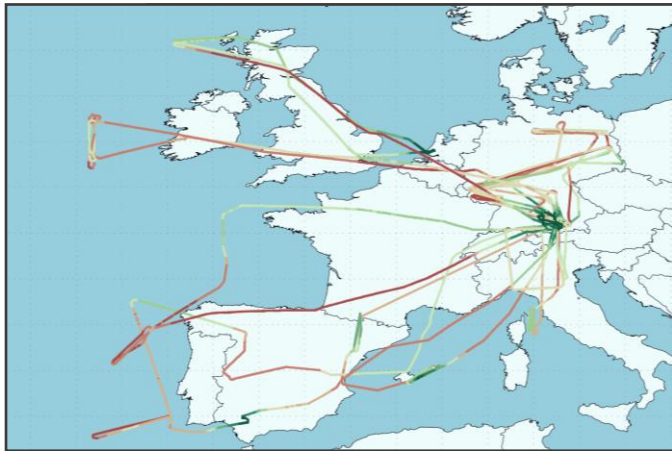


Supplement: IAGOS DATA ANALYSIS STRATEGY PILLARS

- (1) the distribution of RH_{ice} from in-situ observations**
and the subsequent determination of areal fractions of PCCR and ISSR;
- (2) fulfilment of Schmidt-Appleman criterion using in-situ measured temperature**
for the identification of regions where contrails will form;
- (3) cirrus cloud coverage from ERA5 cloud ice water content (CIWC)**
which can reliably capture cloud presence by the assimilation of comprehensive satellite radiance measurements; and
- (4) the distinction between areas covered by clear sky, subvisible or visible clouds**
by means of a CIWC threshold value separating subvisible from visible cirrus.

Supplement: Contrails in clouds – Occurrence conditions

HALO ML-Cirrus



Normalised RH_{ice} occurrence frequency distributions in 5% RH_{ice} bin width for contrail cirrus and natural cirrus.

Contrail-cirrus already exist at slight subsaturation with $RH_{ice} \geq 90\%$
 \Rightarrow Potential Contrail-Cirrus Region PCCR

Li et al., ACP 2023