CONTRAIL EVOLUTION AND LIFETIME

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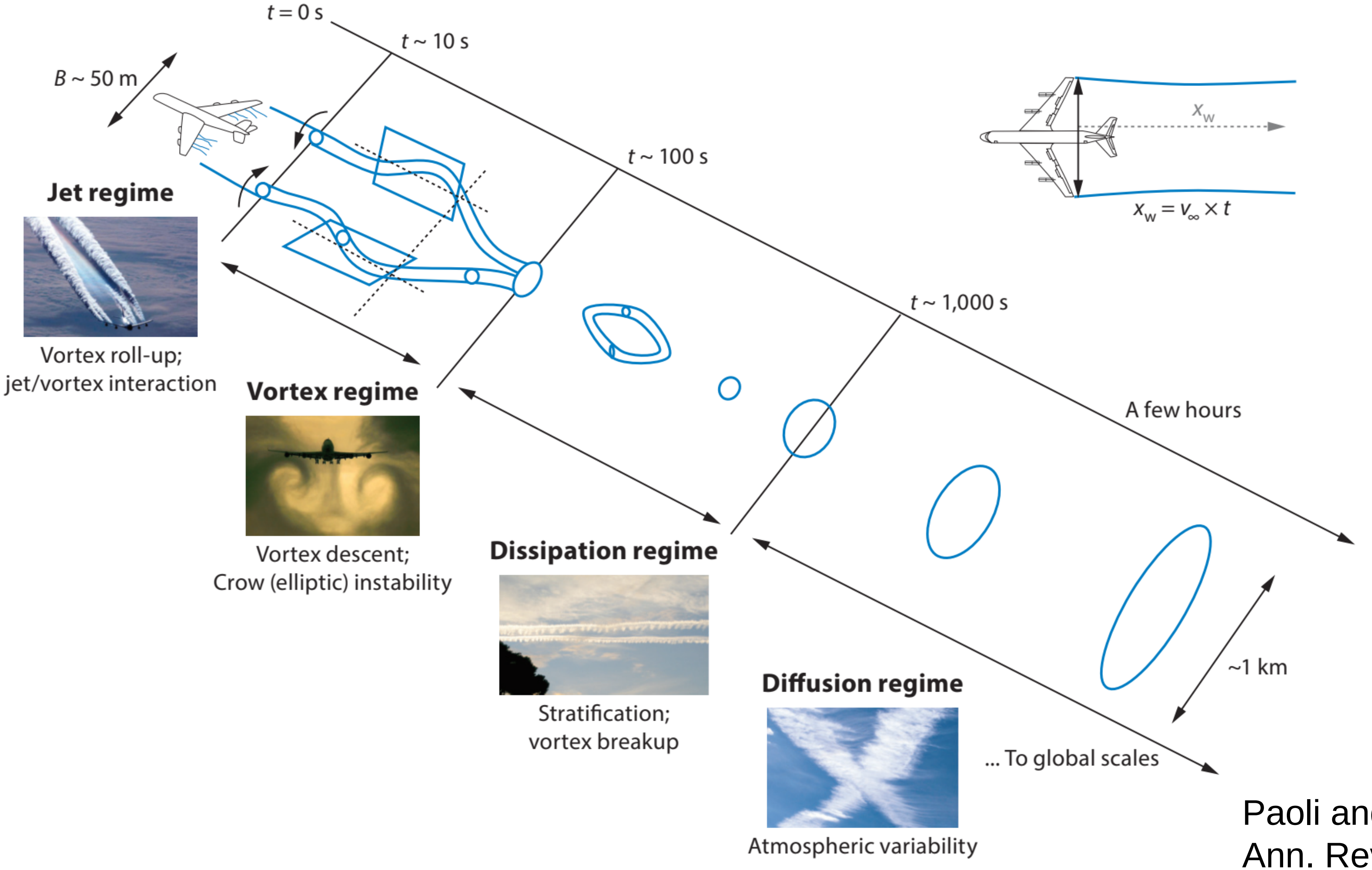
PHASES OF CONTRAIL EVOLUTION

Recap of contrail formation (see Feijia‘s lecture)

- Contrail formation proceeds in approx. 1/3 s
- Condensation on emitted soot particles when water saturation is reached and exceeded
- The number of ice particles formed depends on the number of soot particles emitted
- New results indicate a larger role of nvPM in contrail formation even under soot rich conditions.
- If no soot is emitted (e.g. LH2), condensation proceeds on ambient particles and co-emitted nvPM.

Phases (regimes) of contrail evolution



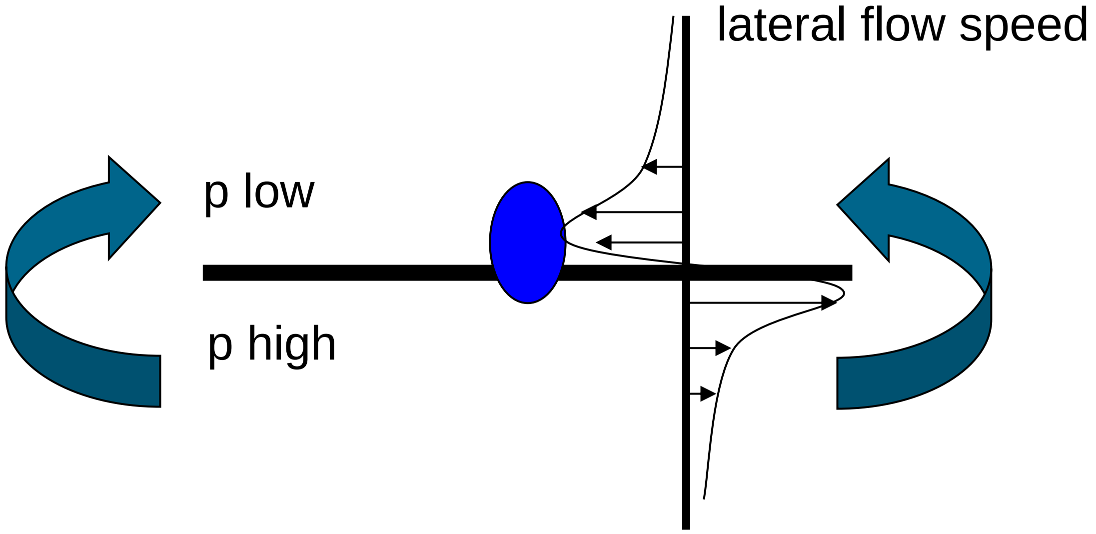
Paoli and Shariff,
Ann. Rev. Fluid Mech. 2016

Contrail evolution
1. Jet phase

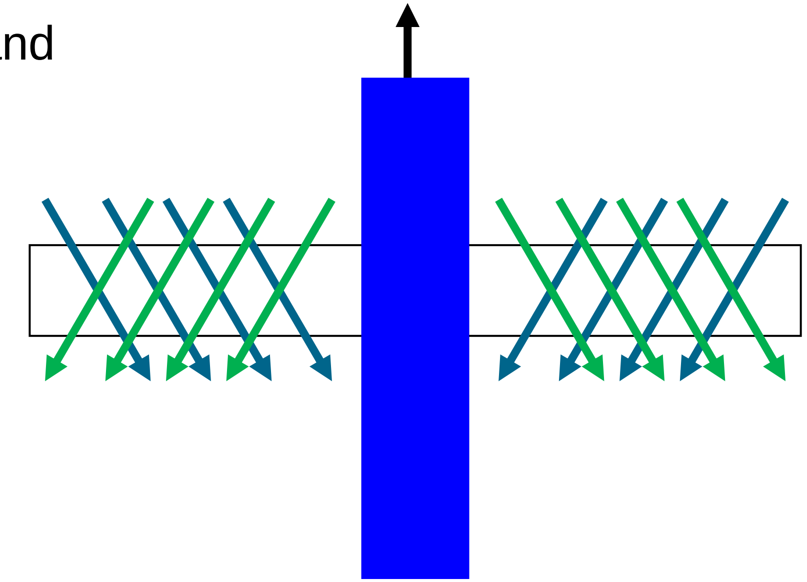
- Jet phase (0-20 s)
- The exhaust leaves an engine with quite high speed relative to the ambient air, forming a jet. At the boundary between the jet and the ambient air the large speed gradient causes friction, hence turbulent mixing leads to an increase of the jet plume cross section and decelerates the jet.
- The plume cross section increases nearly linearly with time.
- The mixing with ambient air causes temperature to decrease within the plume until the jet phase ends.
- The jet phase ends when the plume evolution starts to become controlled by the wing vortices.

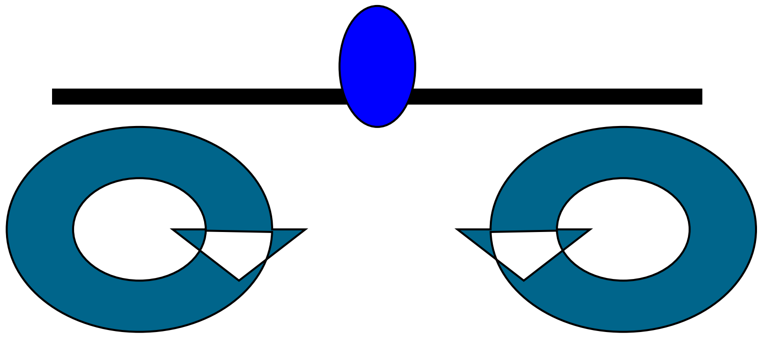
Foto: D. Klatt, Oldenburg

Contrail evolution
2. Vortex phase – formation of a vortex pair



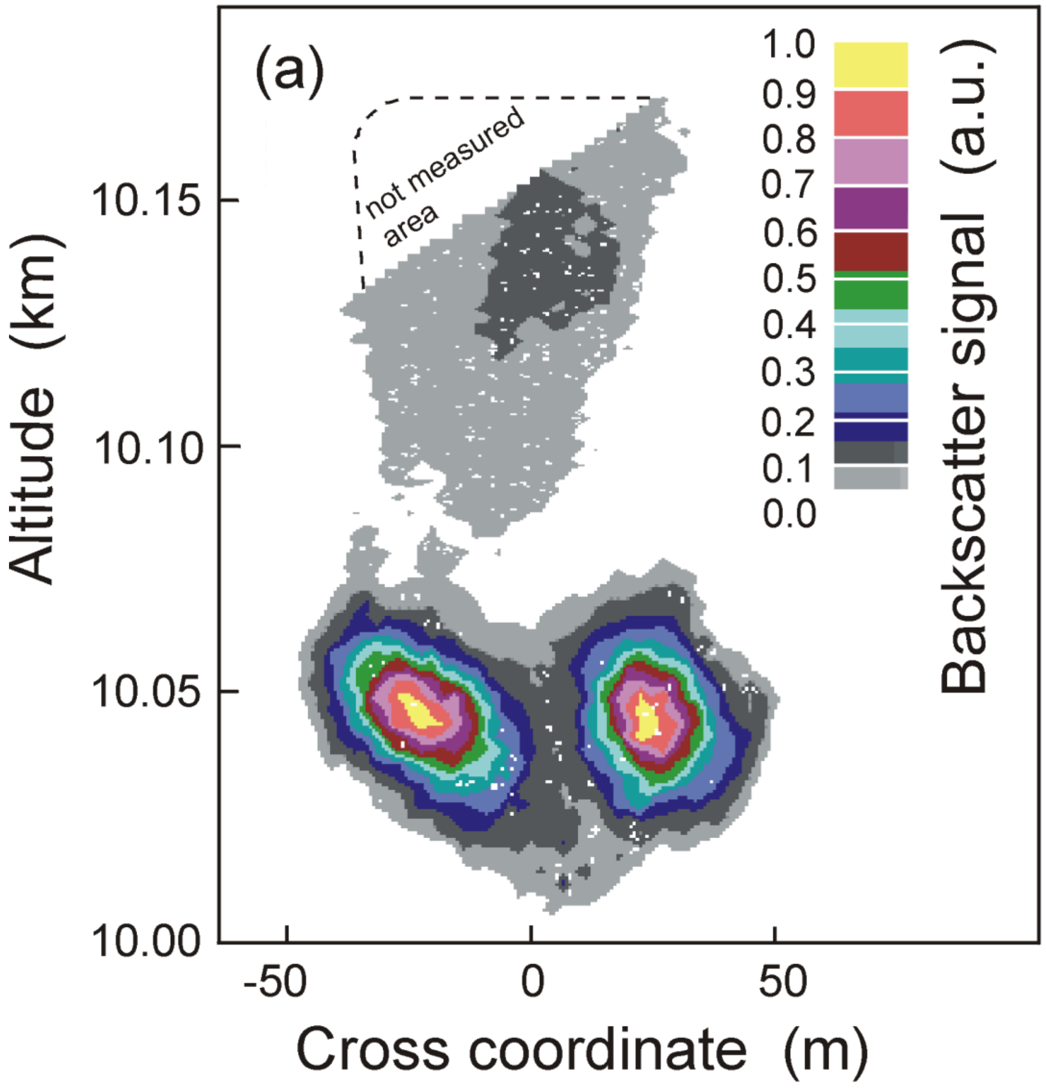
air flow above and
below wing





Contrail evolution
2. Dynamics during the vortex phase

- Vortex phase (20 – 150 s)
- Interaction of the vortex tubes leads to a descent of approx. 2 m/s, up to 300-500 m;
- Exhaust gases and ice crystals are captured and confined inside the vortex tubes;
- Descent leads to adiabatic compression and this leads to partial evaporation of the ice crystals;
- Descent and counter-rotation of the vortex tubes leads to the formation of secondary vortices above the primary vortices;
- Inhomogeneity of the air leads to instability and ultimately to vortex decay, with interesting dynamic effects.



Sussmann & Gierens, JGR, 2001

Contrail evolution
3. Vortex decay - examples

Fotos von Anonymous, Klatt, und Gao

Contrail evolution
4. Dispersion phase

- Dispersion phase (minutes to hours)
- Aircraft-induced dynamics ends, the dynamics of the atmosphere and its thermodynamic properties determines the further development;
- Wind shear spreads the contrail horizontally (typical value: pedestrian speed);
- Contrails are advected with the wind;
- Ice crystals grow in ice-supersaturated conditions until they get heavy enough to sediment and sublimate in drier air
- or large-scale subsidence or decoupling of contrail and ISSR lead to contrail termination.

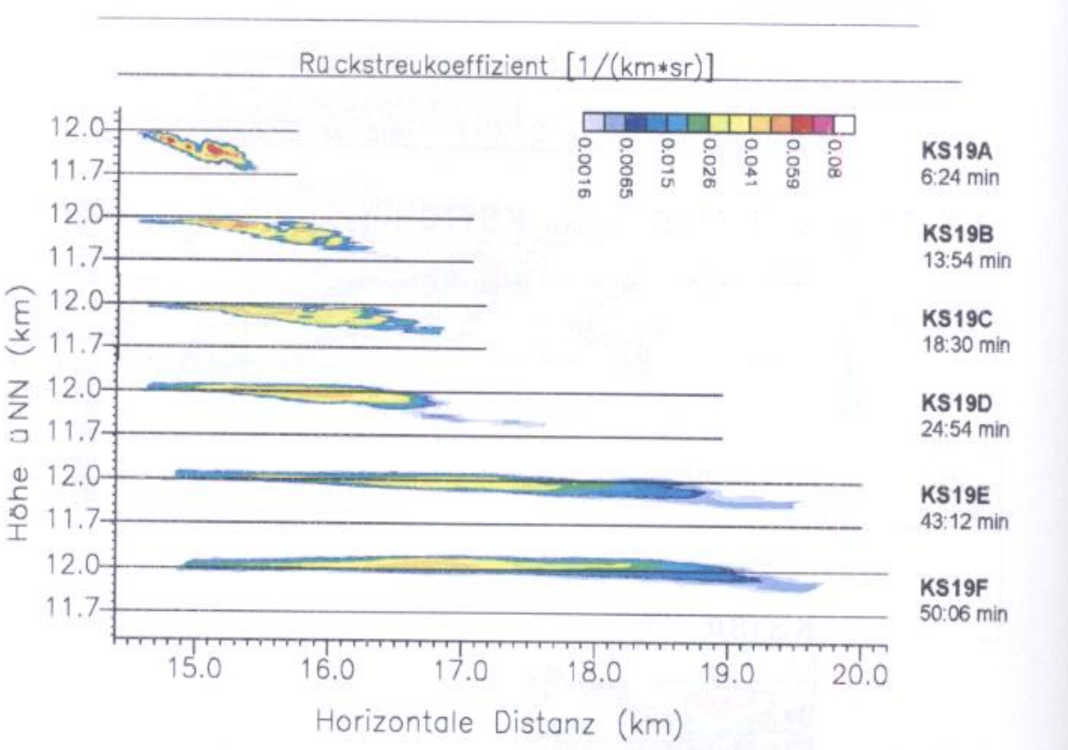


Abbildung 3.19: Breitenwachstum des Kondensstreifen **KS19** in sechs zeitlich aufeinanderfolgenden Querschnitten im Dispersionsregime.

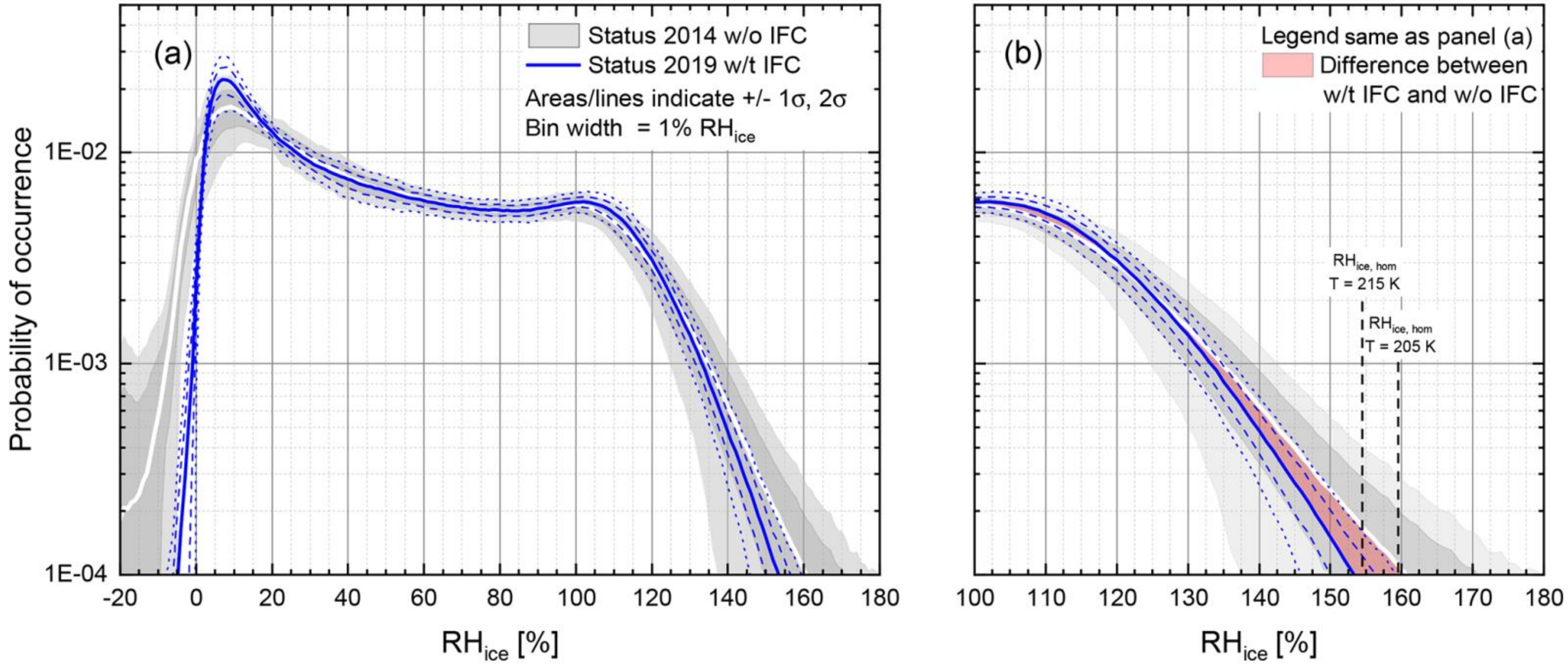
V. Freudenthaler, Dissertation, 2000

ICE SUPERSATURATION

Ice supersaturated regions (ISSRs)

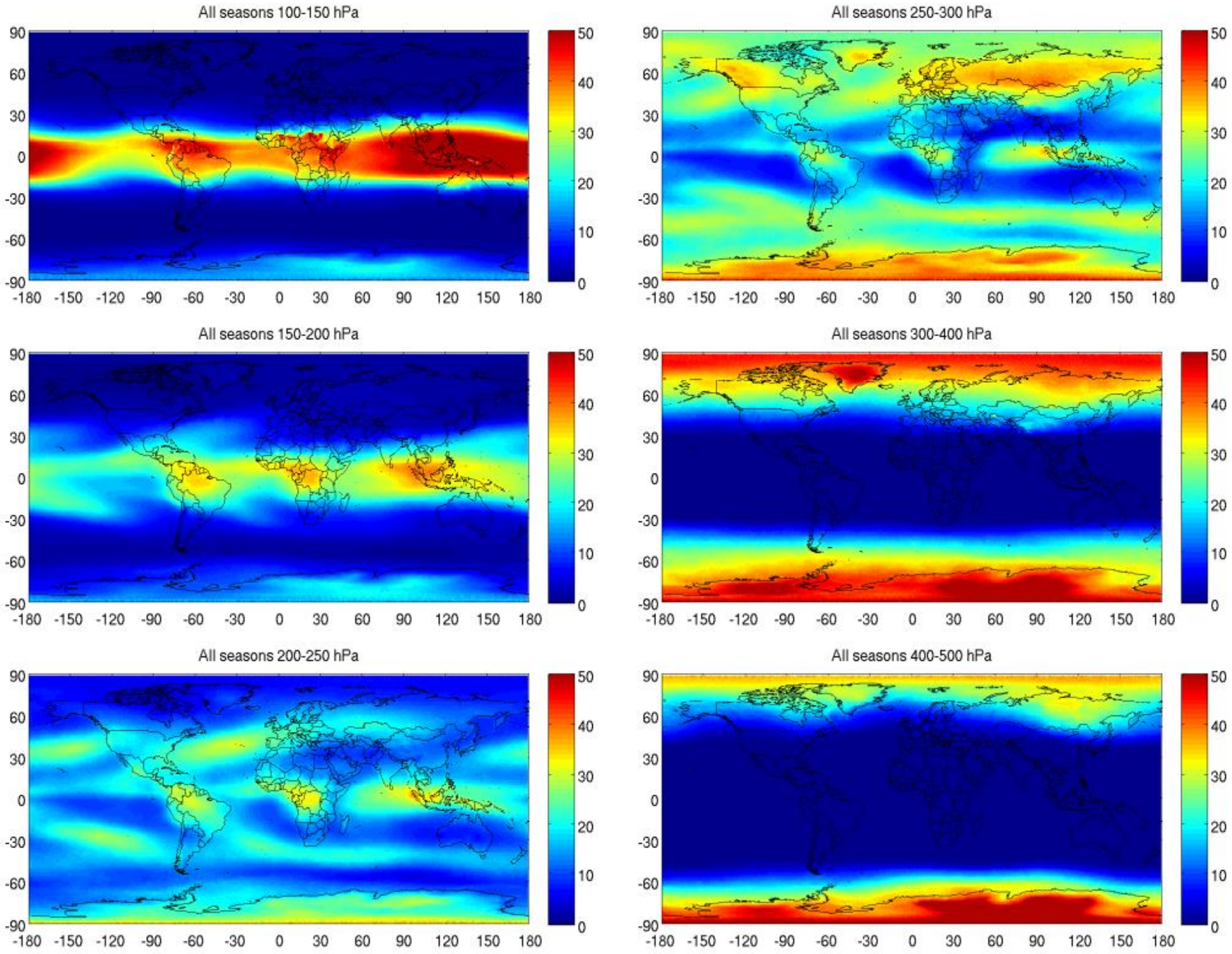
Foto: N. Dotzek

- Only persistent contrails impact climate;
- Persistence requires ice supersaturation (RHi ≥ 100%);
- Ice supersaturation is frequent at 0-200 hPa beneath the tropopause;
- About 10-15% of flight distances in ISSRs



MOZAIC Data 1995-2010
Petzold et al. 2021

Climatology of ISS



Lamquin et al., 2012, from AIRS sat. data

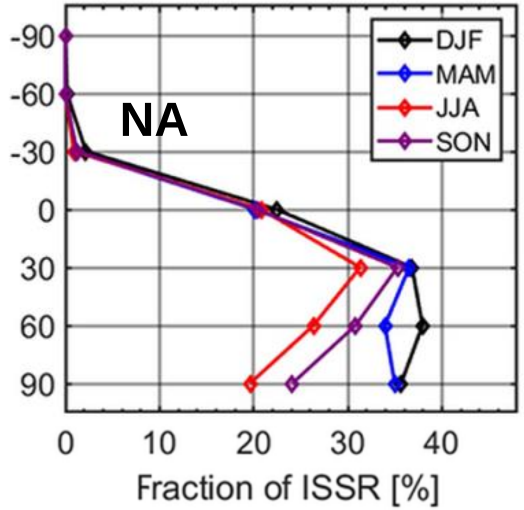
Climatology of ISS

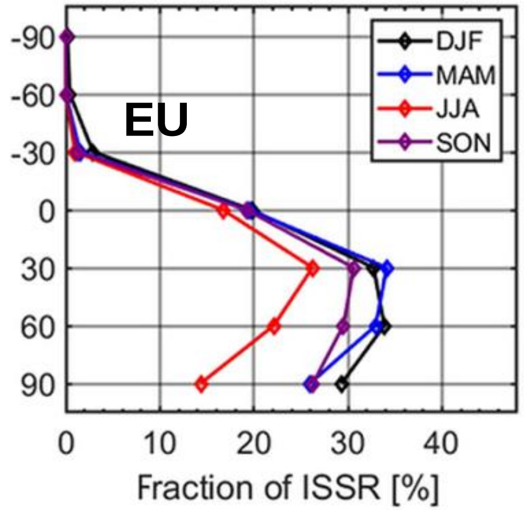
- Vertically
  - ISS is most frequent directly below the tropopause, rare above the tropopause,
  - higher frequency in winter than in summer

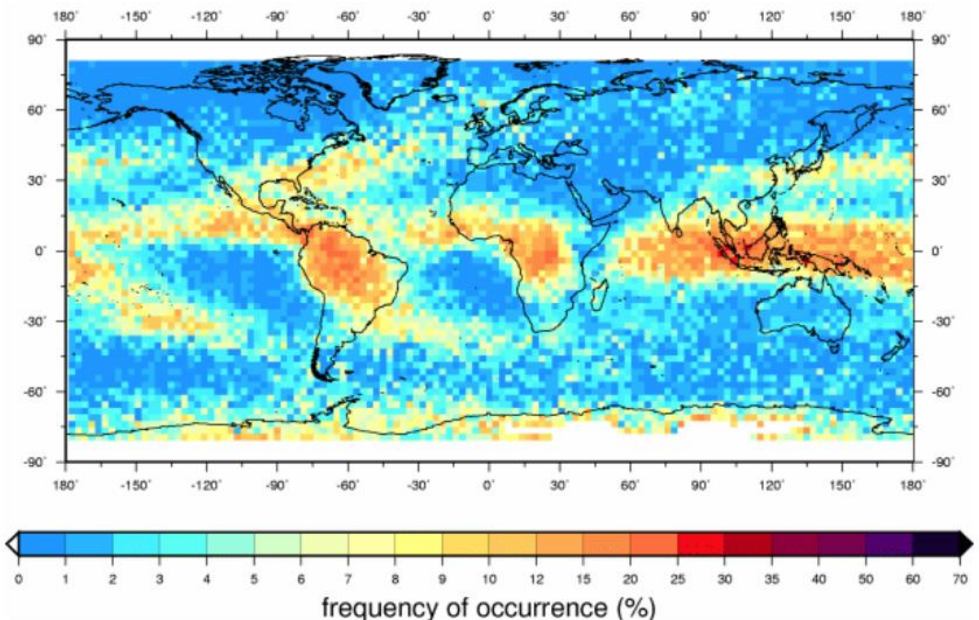
    (Petzold et al., 2020, IAGOS data, similar to Spichtinger et al. 2003, RS Lindenberg data)

- Horizontally
  - The horizontal distribution of ISSRs varies with the pressure altitude (tropopause) and saisonally.
  - Particularity over Antarctica

    (Spichtinger et al., 2003, MLS data)

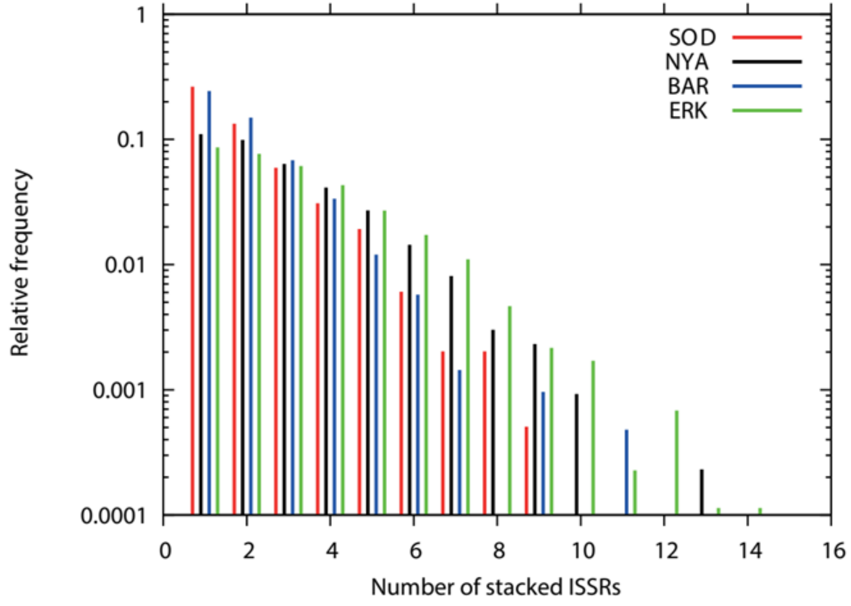






Properties of ISSRs

- The degree of ice supersaturation is exponentially distributed (mean ~ 15%)
- ISSRs are a few K colder than their environment
- ISSRs are moister than their environment (~× 2)
- A typical pathlength through ISSRs is 150 km, but with very wide variability
- ISSRs are on the order of 500 m thick, but again with wide variability
- ISSRs are inhomogeneous objects, thus estimations of horizontal and vertical extension depend on the spatio-temporal resolution of the humidity sensor



Gierens et al., MZ, 2020

CONTRAIL LIFETIMES

Contrail termination mechanisms

Contrail lifetime is constrained by

- the sedimentation of ice crystals into lower, subsaturated levels
- the blowing out of the ice crystals from the parent ISSRs by the wind
- the reduction of supersaturation down to subsaturation due to large-scale subsidence

sedimentation time-scale τ_{sed}

synoptic time-scale τ_{syn}

combined time-scale τ_{com}

Time-scale for sedimentation (τ_{sed}) of ice crystals in cirrus and contrails

… in theory

equations by Spichtinger and Gierens, 2009

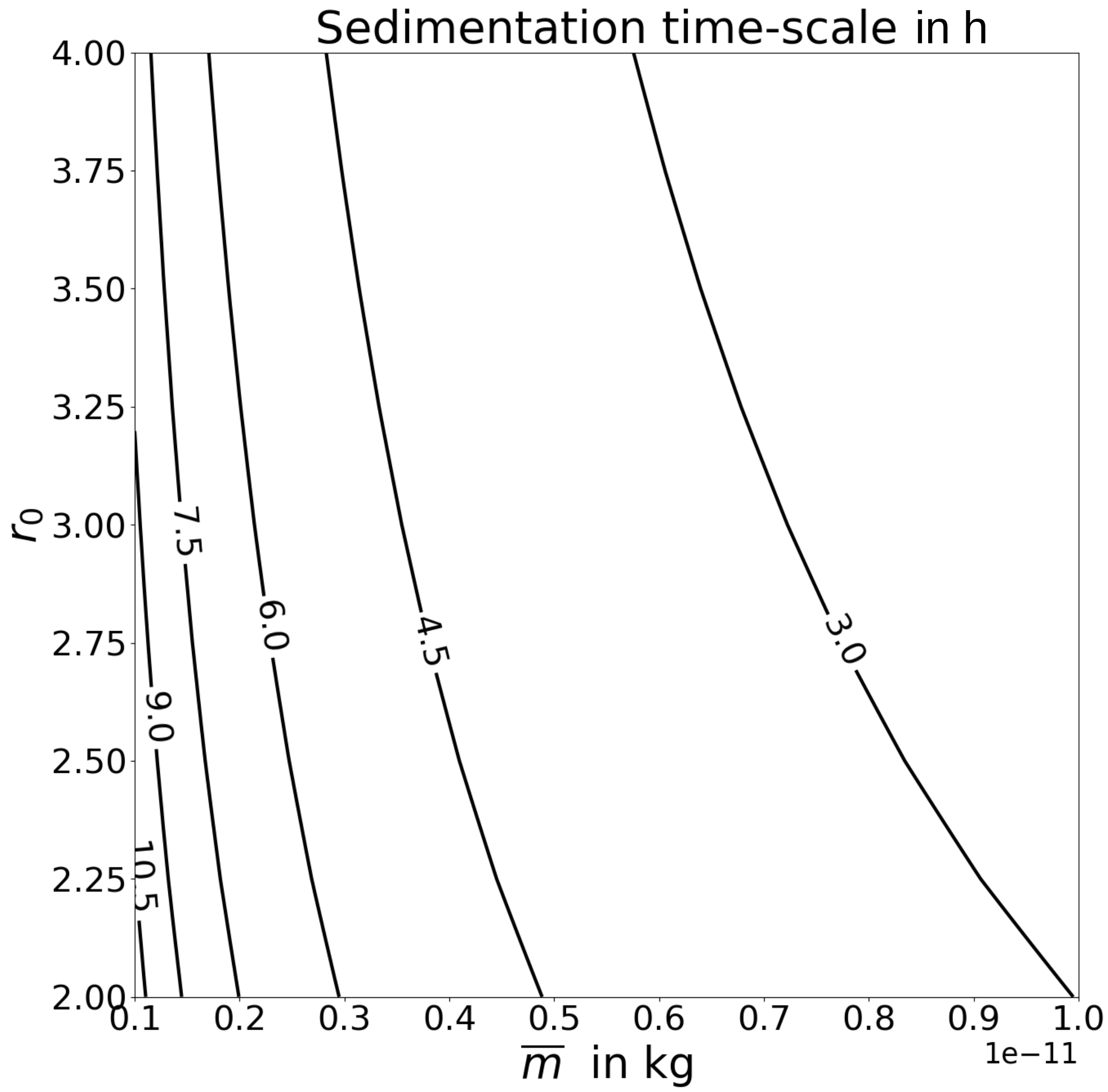
contrail thickness

$$\tau_{\text{sed}} = \frac{H}{\gamma \cdot \overline{m}^{0.57} \cdot r_0^{0.45}}$$

constant

width of the lognormal distribution

mean ice crystal mass / mean of the lognormal distribution



Hofer and Gierens, 2025b

Kinematics of ISSRs

Contrails

- consist of (material) ice crystals

↓

move with the wind

- contrails may be driven out of the ISSR → terminates their existence

Ice supersaturation

- is an immaterial feature

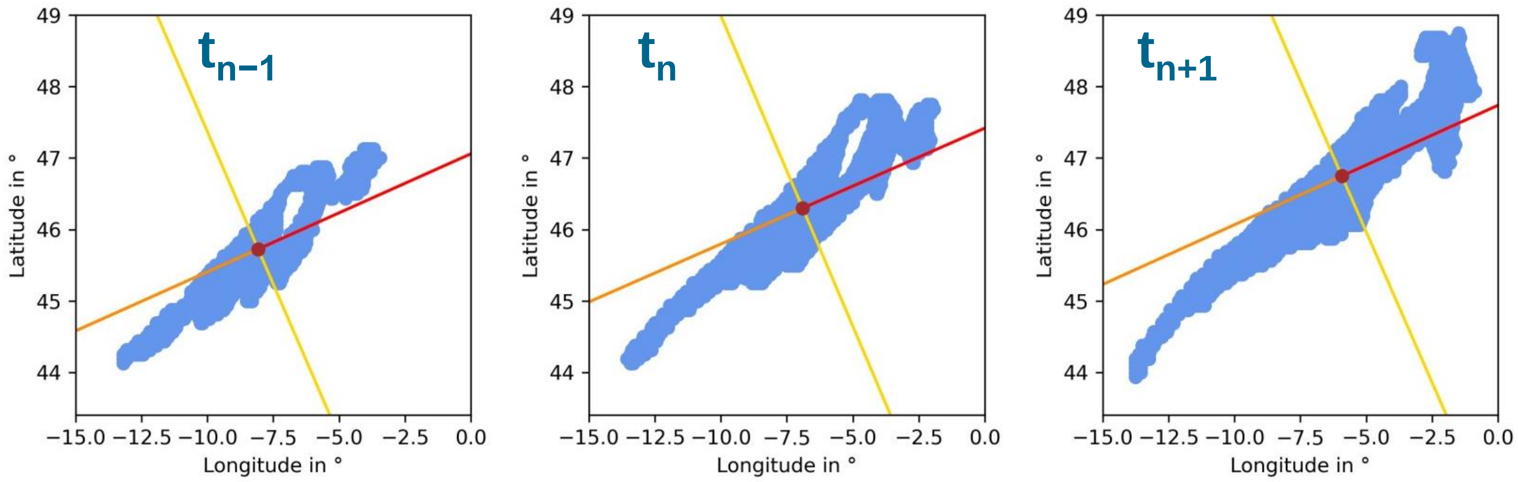
↓

does not generally move with the wind

- lifetime is limited by the dynamics of the atmosphere

differences between the wind and the motion of ISSRs

Identification of ISSRs in weather model data



Hofer and Gierens, 2025a

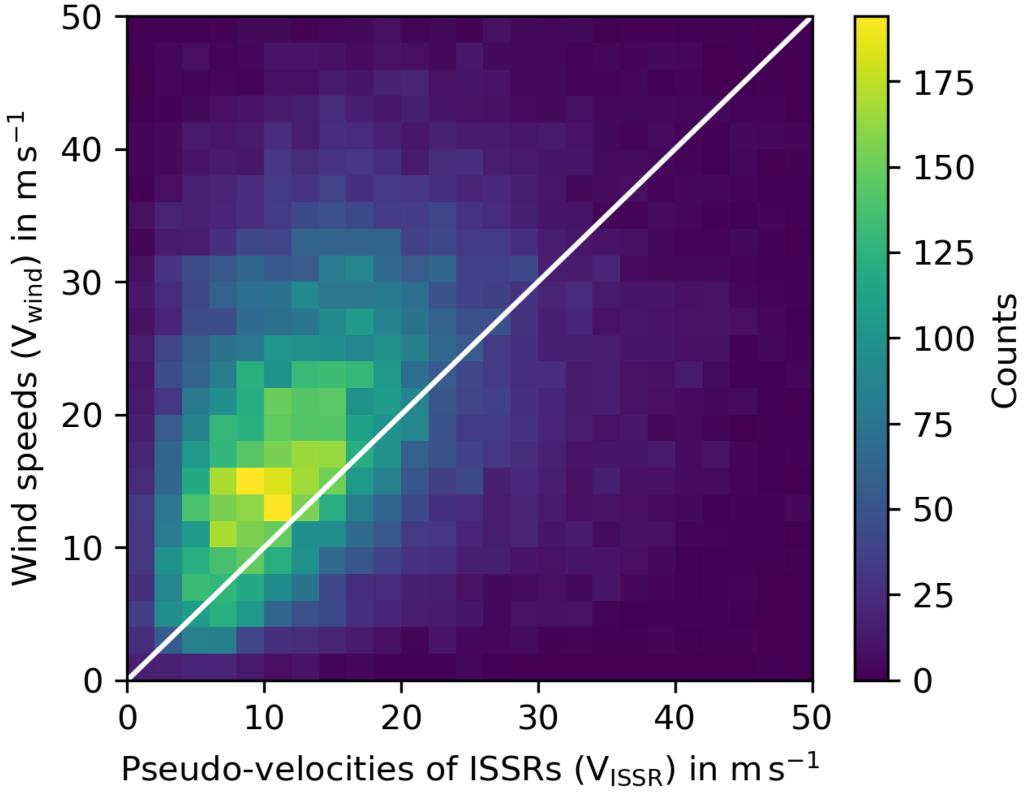
- **location of the ISSR:** centre of probability (COP)

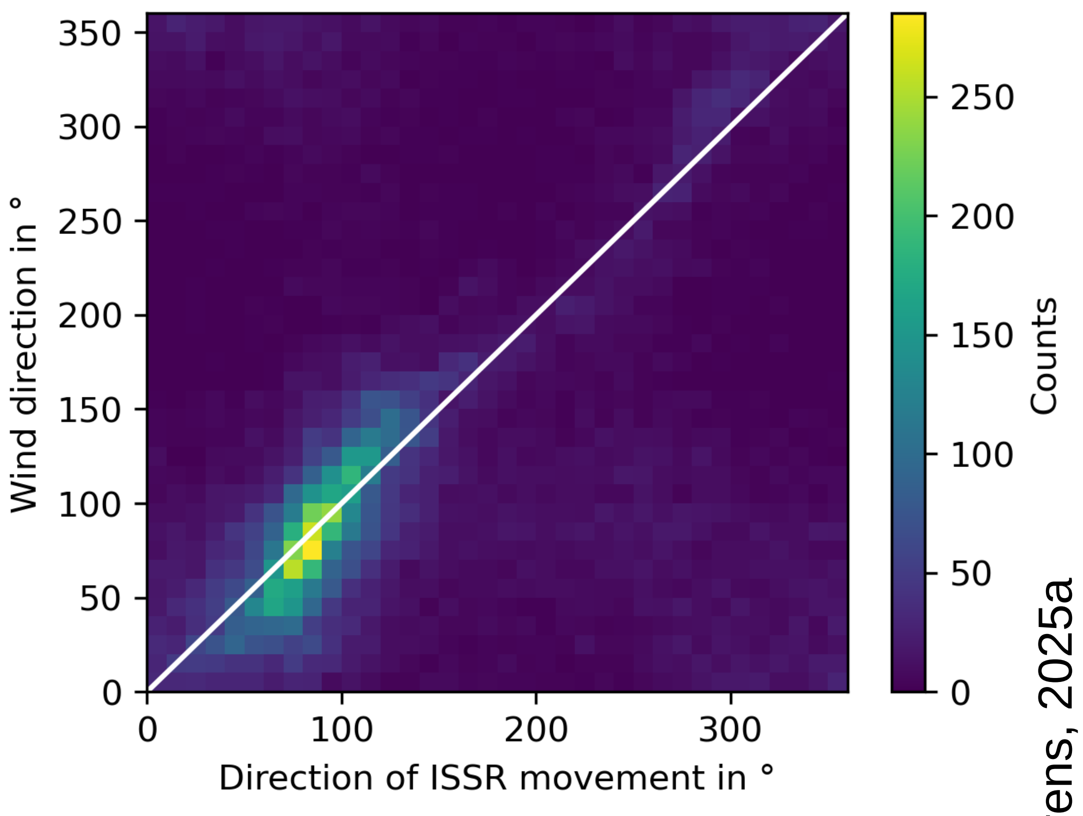
$$x_{\mathrm{COP}} = \frac{\sum_{n=1}^{N} PPC_{\mathrm{prob}_n} \cdot x_n}{\sum_{n=1}^{N} PPC_{\mathrm{prob}_n}} \quad \text{and} \quad y_{\mathrm{COP}} = \frac{\sum_{n=1}^{N} PPC_{\mathrm{prob}_n} \cdot y_n}{\sum_{n=1}^{N} PPC_{\mathrm{prob}_n}}$$

- **principal axes of an ISSR:** eigenvectors of covariance matrix

$$\Theta = \begin{pmatrix} \sum_{n=1}^{N} PPC_{\mathrm{prob}_n} \cdot (x_n - x_{\mathrm{COP}})^2 & \sum_{n=1}^{N} PPC_{\mathrm{prob}_n} \cdot (x_n - x_{\mathrm{COP}}) \cdot (y_n - y_{\mathrm{COP}}) \\ \sum_{n=1}^{N} PPC_{\mathrm{prob}_n} \cdot (x_n - x_{\mathrm{COP}}) \cdot (y_n - y_{\mathrm{COP}}) & \sum_{n=1}^{N} PPC_{\mathrm{prob}_n} \cdot (y_n - y_{\mathrm{COP}})^2 \end{pmatrix}$$

2D-histograms of speeds and directions of motion





Hofer and Gierens, 2025a

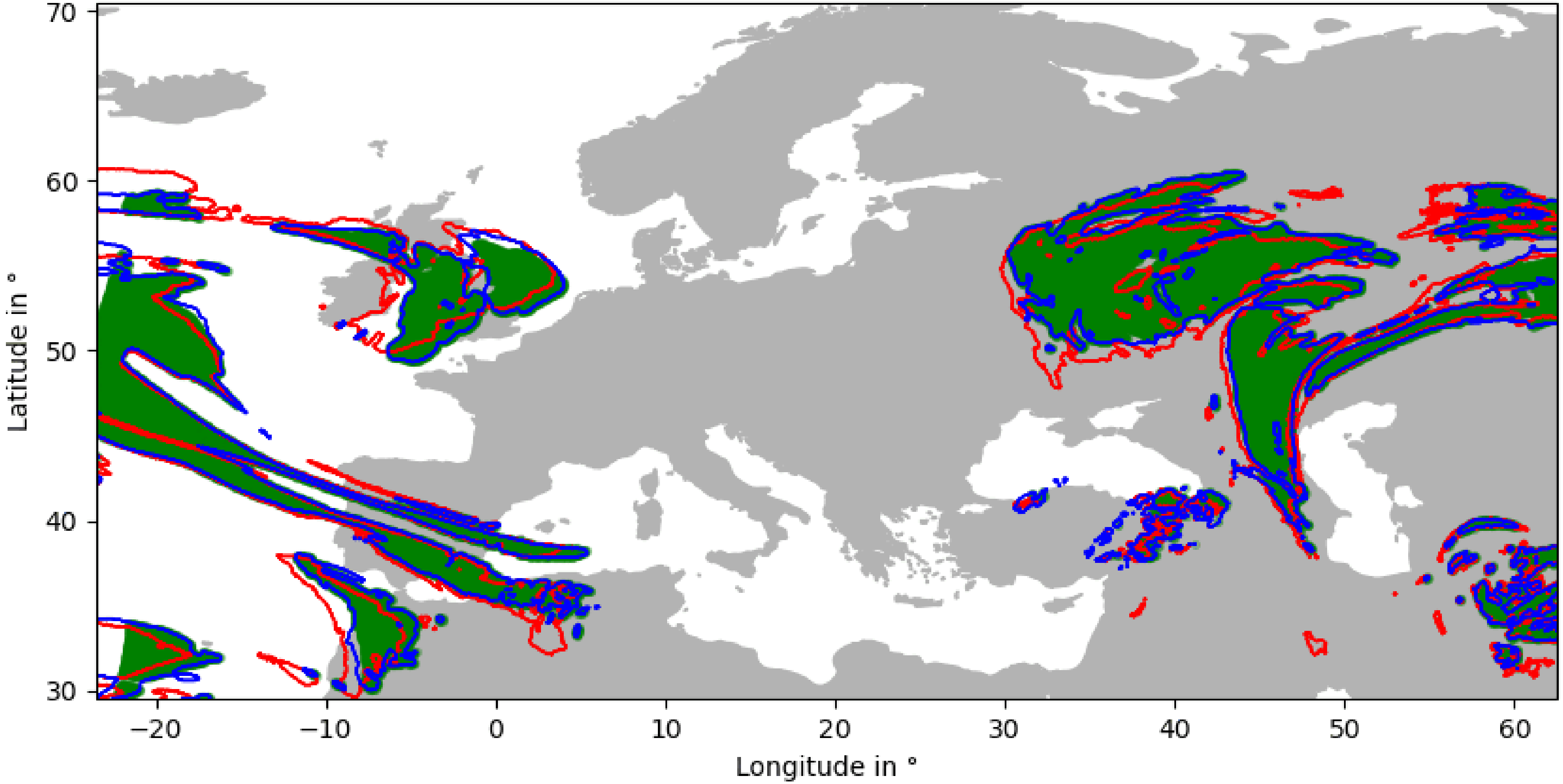
→ the wind moves on average a bit faster then the ISSRs, but usually both move in similar directions (mostly to the east).

→decoupling of ISSRs and embedded contrails.

Time-scale for contrails to leave an ISSR with the wind (τ_{syn})

Case 1:

April 18, 2024 (12 UTC + 2h up to + 25h) at 250 hPa



PPC=1 regions at the beginning

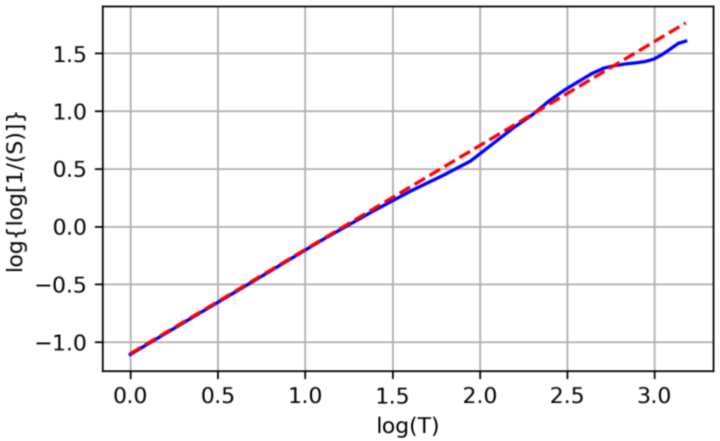
ISSRs in the following hours

Initial PPC=1 grid points that are still inside ISSRs

Time-scale for contrails to leave an ISSR with the wind (τ_{syn})

Survival function on Weibull paper

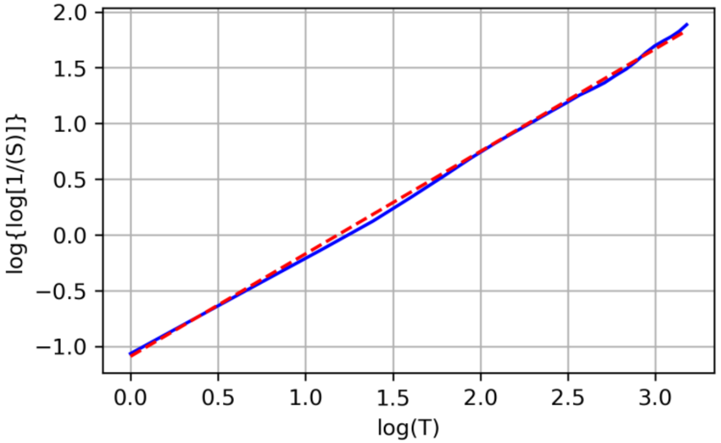
Case 1:
April 18, 2024



$g = 0.9 \cdot x - 1.10$

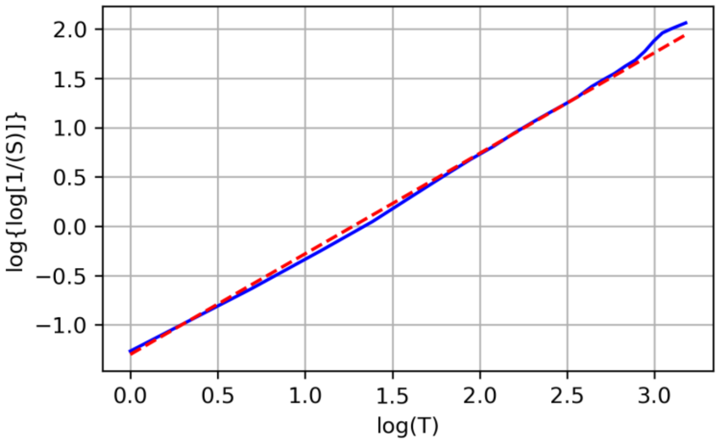
k: slope
β: intercept

Case 2:
May 01, 2024



$g = 0.92 \cdot x - 1.09$

Case 3:
May 24, 2024



$g = 1.02 \cdot x - 1.30$

$$\tau_{syn} = T_0 = T_u \cdot \exp[-(\beta/k)] \approx 4\text{h}$$

Time-scale for contrails to leave an ISSR with the wind (τ_{syn})

… in theory

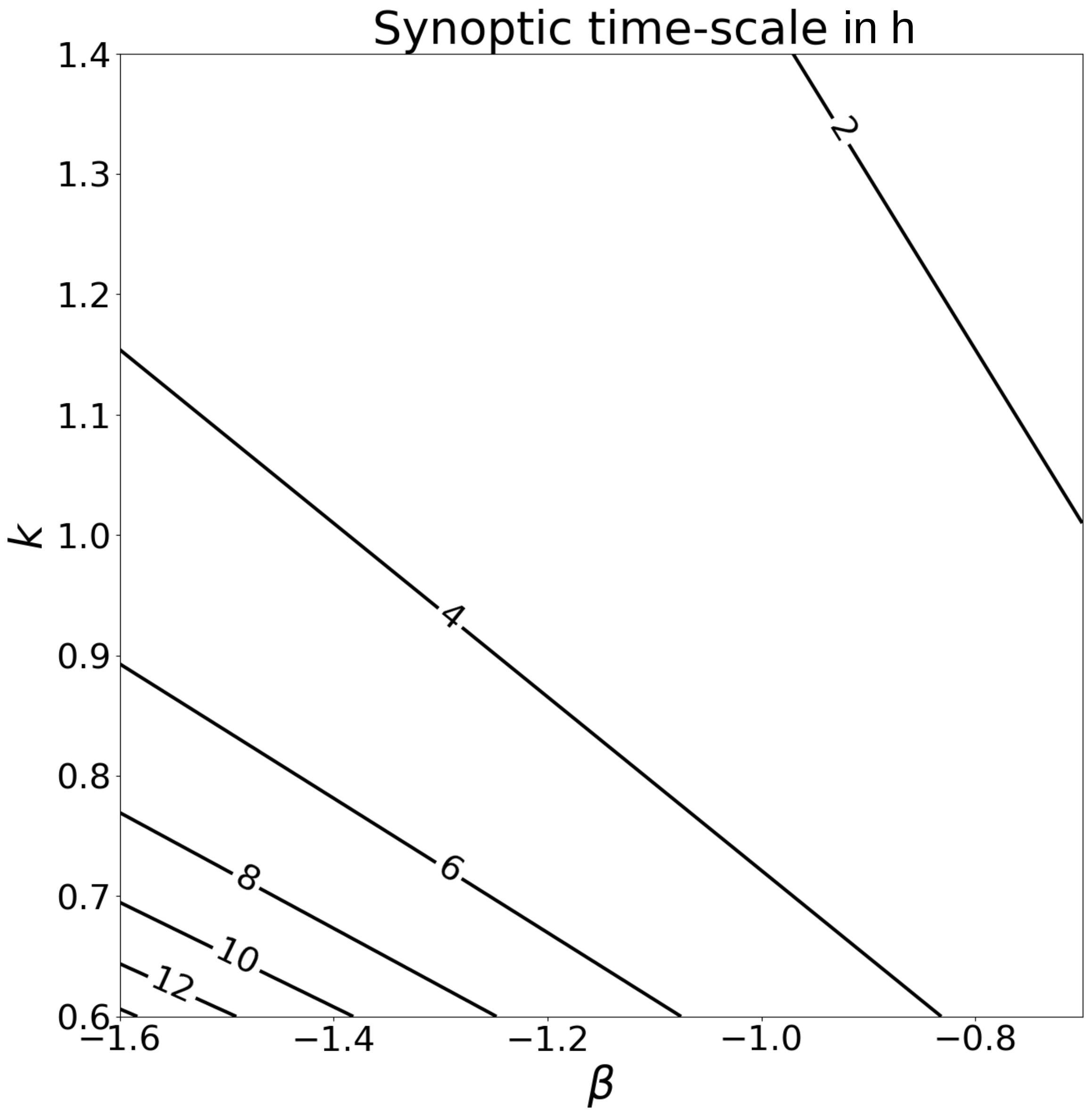
the time (T) an air parcel resides within an ISSR is Weibull-distributed:

$$S(T) = 1 - F(T) = exp[-(T/T_0)^k]$$

Survival function

cumulative distribution function of T

time-scale for leaving an ISSR = time, where $S(\tau_{syn}) = e^{-1}$, $\tau_{syn} = T_0$



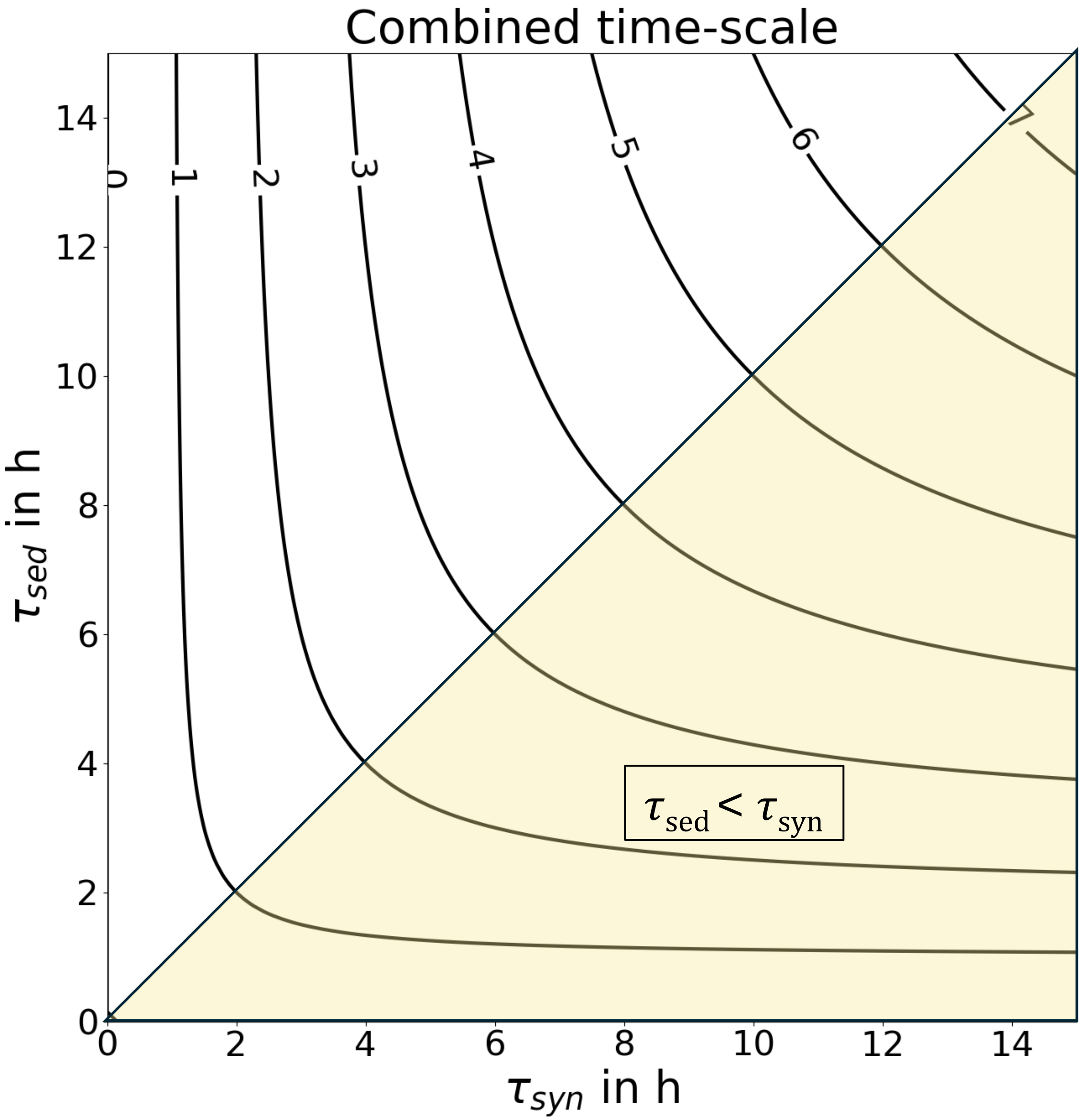
The combined time-scale (τ_{comb})

$$\frac{1}{\tau_{\text{com}}} = \frac{1}{\tau_{\text{sed}}} + \frac{1}{\tau_{\text{syn}}}$$

$$\tau_{\text{com}} = \frac{\tau_{\text{sed}} \cdot \tau_{\text{syn}}}{\tau_{\text{sed}} + \tau_{\text{syn}}}$$

The combined time scale is half the harmonic mean of the two single time scales. It is thus smaller than the smaller one of the two time scales.

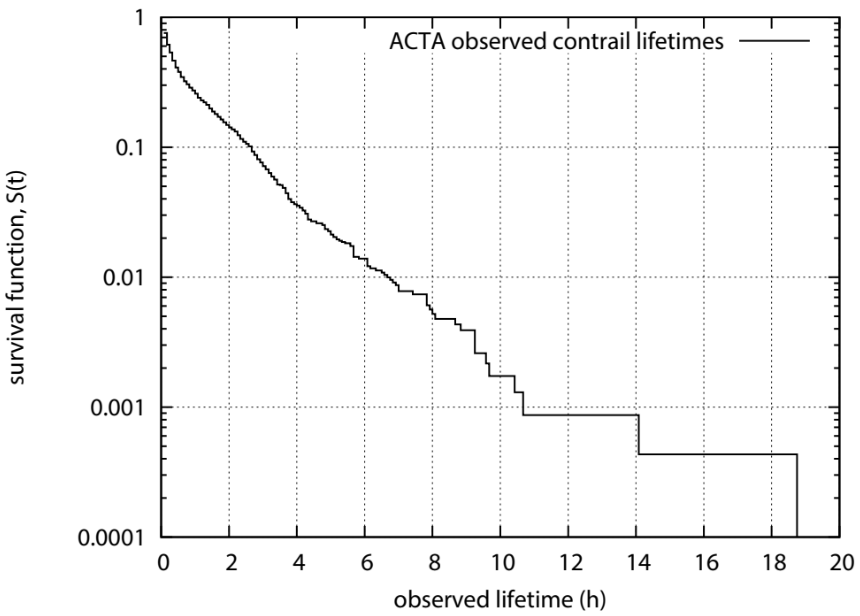
Note that application of SAF to reduce contrail optical thickness and lifetime only gets effective if $\tau_{\text{sed}} < \tau_{\text{syn}}$ results.

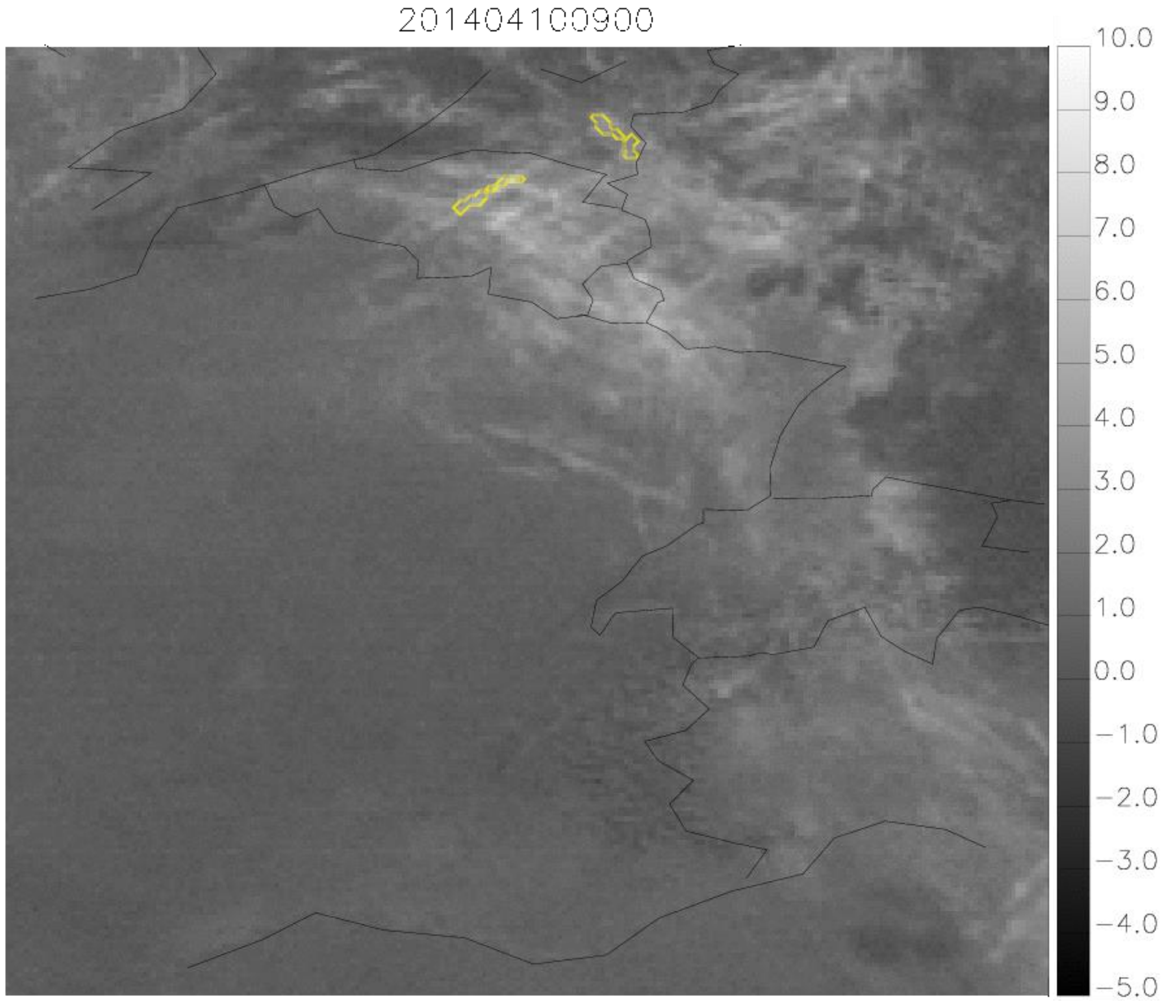


Hofer and Gierens, 2025b

Contrail tracking

- Automatic Contrail Tracking Algorithm (ACTA) by M. Vazquez-Navarro
- Example case 10.04.2014 0900-1405 UTC





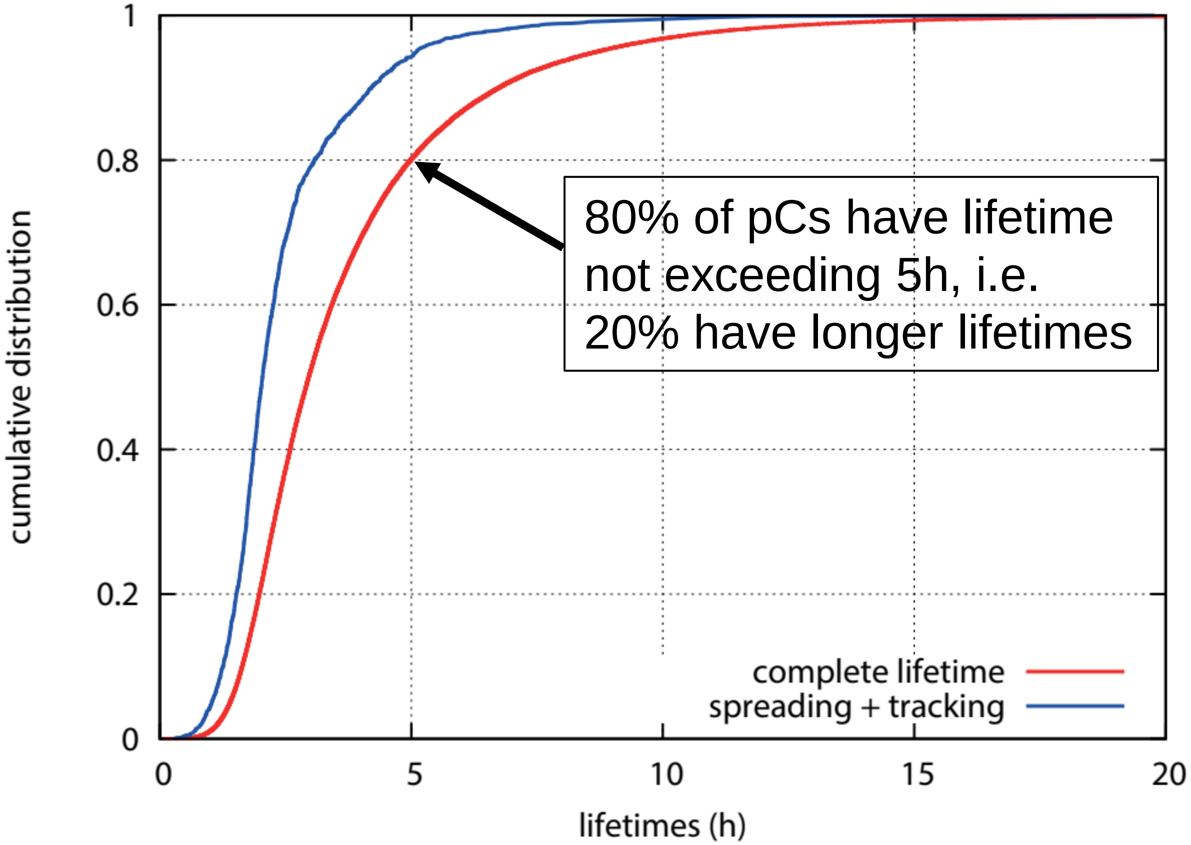
M. Vazquez-Navarro, 2015

Statistical determination of contrail lifetimes

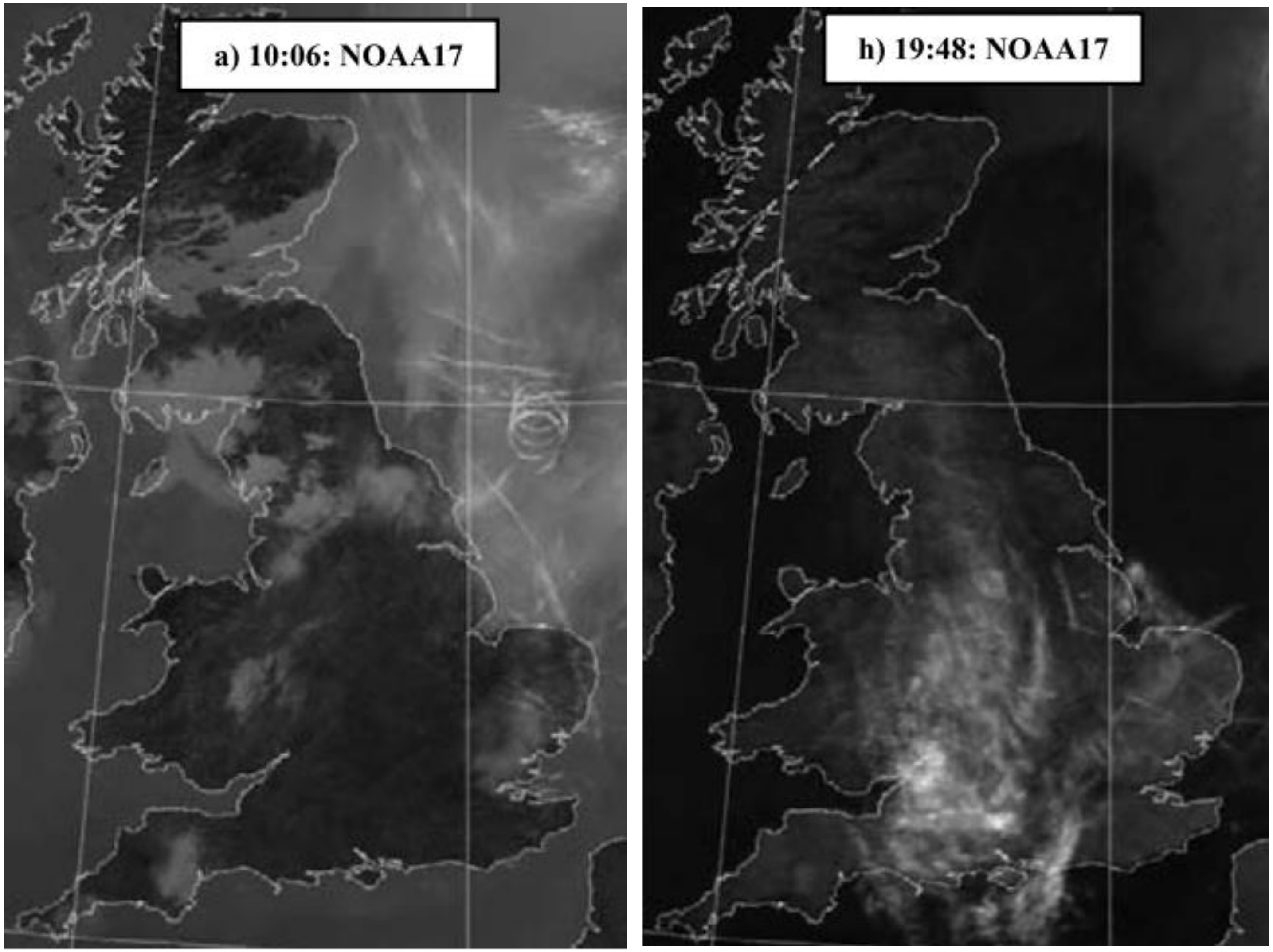
- Survival function ACTA $\rightarrow$ Weibull-d.
- Add unobserved age at appearance in the sat. image and
- make a statistical extrapolation to unobservable spreading at the end:

$$P\{T > \tau + \delta | T > \tau\} = \frac{S(\tau + \delta)}{S(\tau)}$$

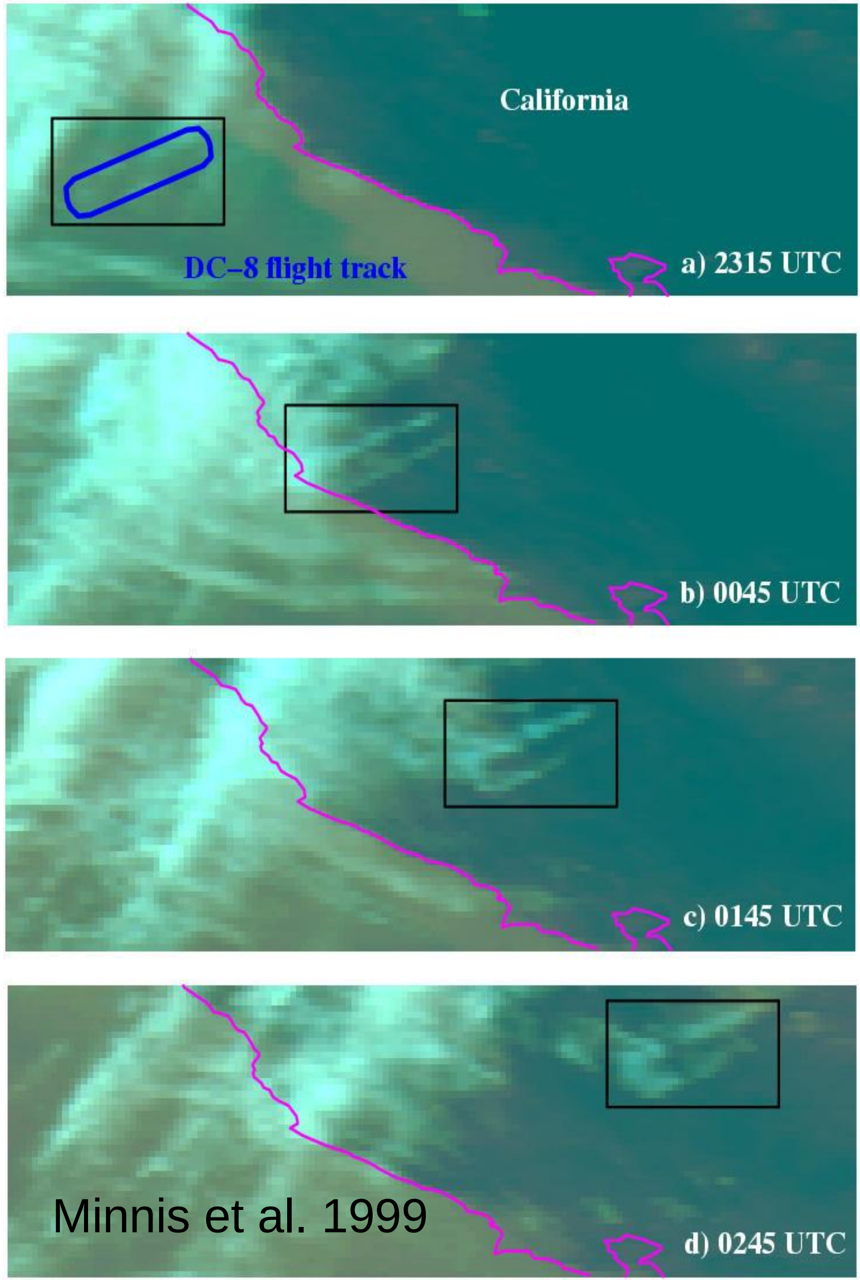
- $\Rightarrow$ lifetime statistics (Gierens & Vazquez-Navarro, 2015)



Extremely longlived contrail examples



Haywood et al., 2009



SUMMARY AND CONCLUSIONS

Summary and conclusions

- Contrail evolution undergoes various phases: Jet phase, Vortex Phase, Dissipation and Dispersion regimes. Persistent contrails survive into the Dispersion regime. Only persistent contrails are relevant for climate.
- 10-15% of contrails are persistent.
- Main contrail termination processes are crystal sedimentation (τ_{sed}), subsidence and decoupling of contrails from their parent ISSR (τ_{syn}).
- Both timescales are a couple of hours.
- For SAF to be an option for contrail effect mitigation, $\tau_{\mathrm{sed}} < \tau_{\mathrm{syn}}$ must result.
- Mean contrail lifetimes are 2-3 hours, but 20% have lifetimes > 5h.