CONTRAIL PREDICTION

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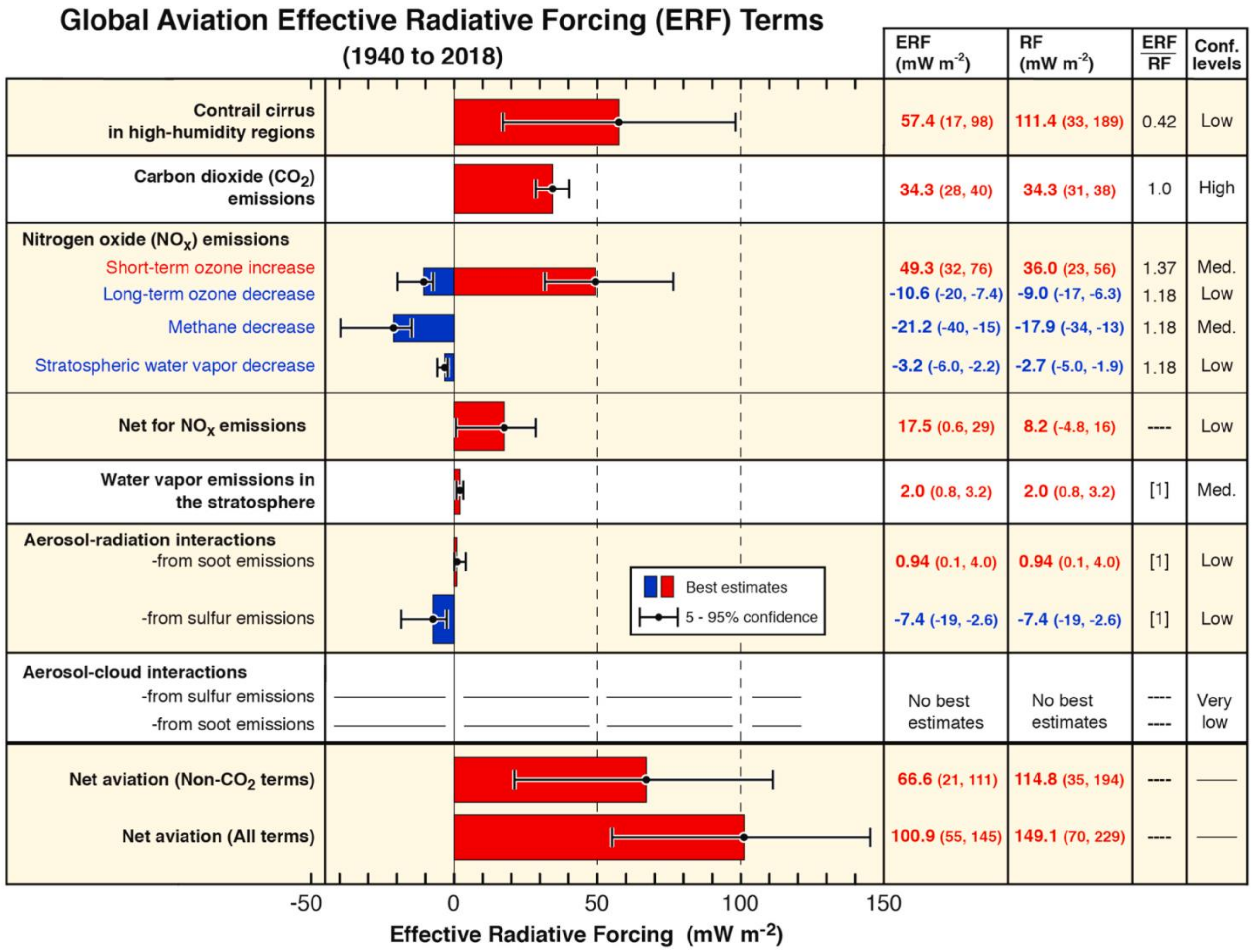
MOTIVATION

Effective radiative forcing (ERF)

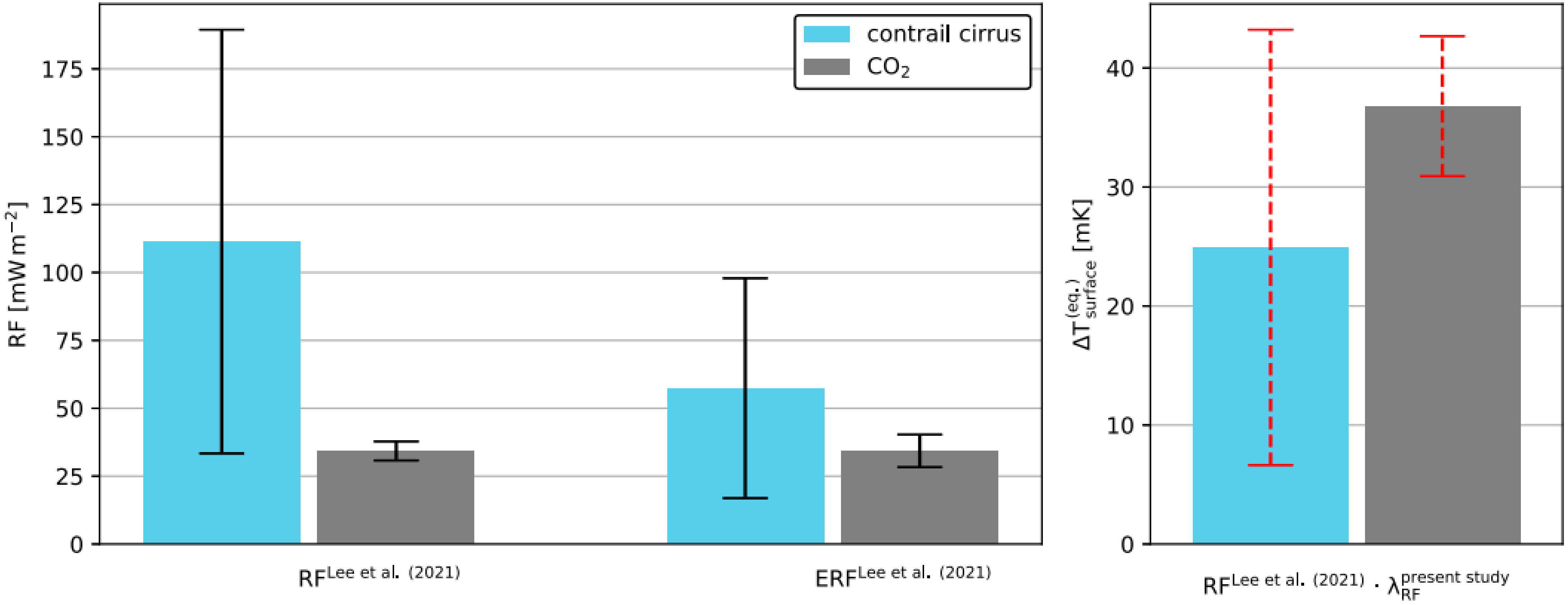


Lee et al., 2021

$$\Delta T = \lambda \ ERF$$

- The non-CO_2 effects contribute at least 2/3 to the total aviation ERF.
- Non-CO_2 effects also occur if alternative fuels are used, in particular H_2.
- The magnitude of the non-CO_2 effects depends on location, altitude and time of the emissions.

Global contrail radiative forcing (mW/m²) and climate impact (mK)



Bickel et al. 2025

Take-away message: Radiative impact ≠ Climate impact (cf. Volker's lecture)

Notes

- This lecture is on the weather forecast aspects of contrail prediction, that is on prediction of temperature and relative humidity (ice supersaturation).
- A reliable weather forecast is prerequisite for tools that are employed for (warming) contrail-avoiding flight planning. These tools have their own issues apart from an unperfect weather forecast. They are out of scope for the present lecture.

THREE FORECAST STEPS

Three necessary steps of contrail prediction

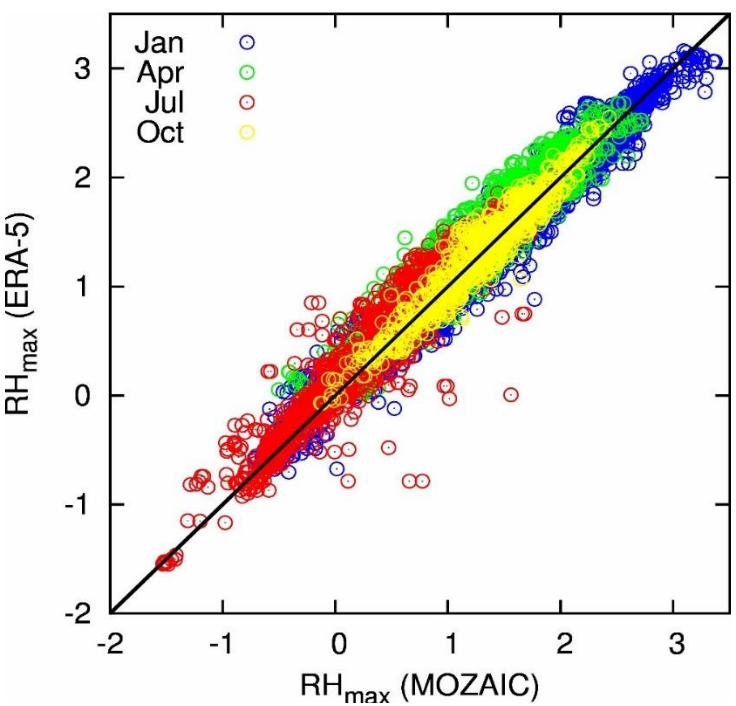
- Three steps with increasing difficulty:

1. Prediction of contrail **formation** ⇨ Schmidt-Appleman Criterion (cf. Feijia's lecture)
2. Prediction of contrail **persistence** ⇨ Forecast of ice supersaturation (ISSR)
3. Prediction of the individual **radiation effect** of a contrail, accumulated during its lifetime, considering the whole scene!

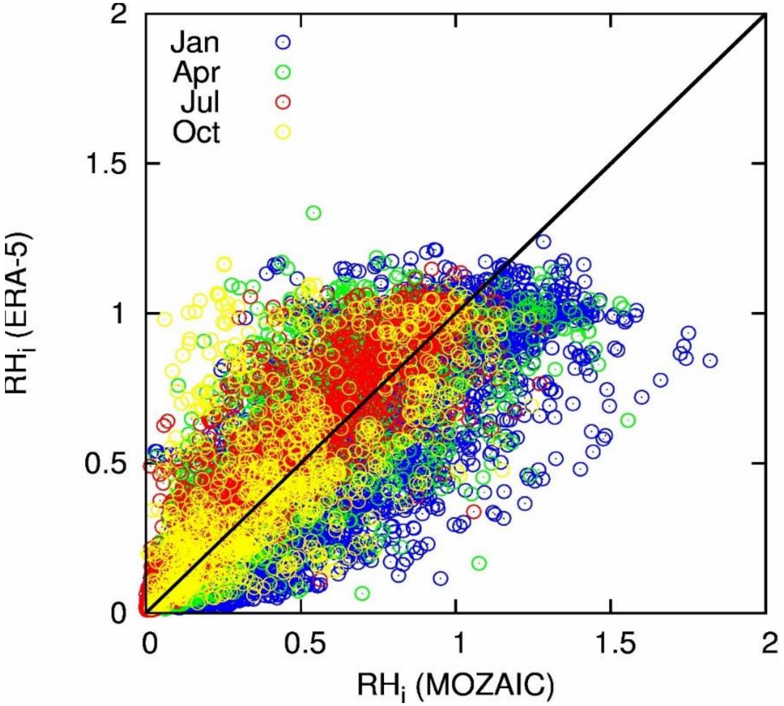
   Out of scope for the current lecture.

Challenges for contrail prediction

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



Contrail persistence criterion (RH_i>1)



Gierens et al. 2020

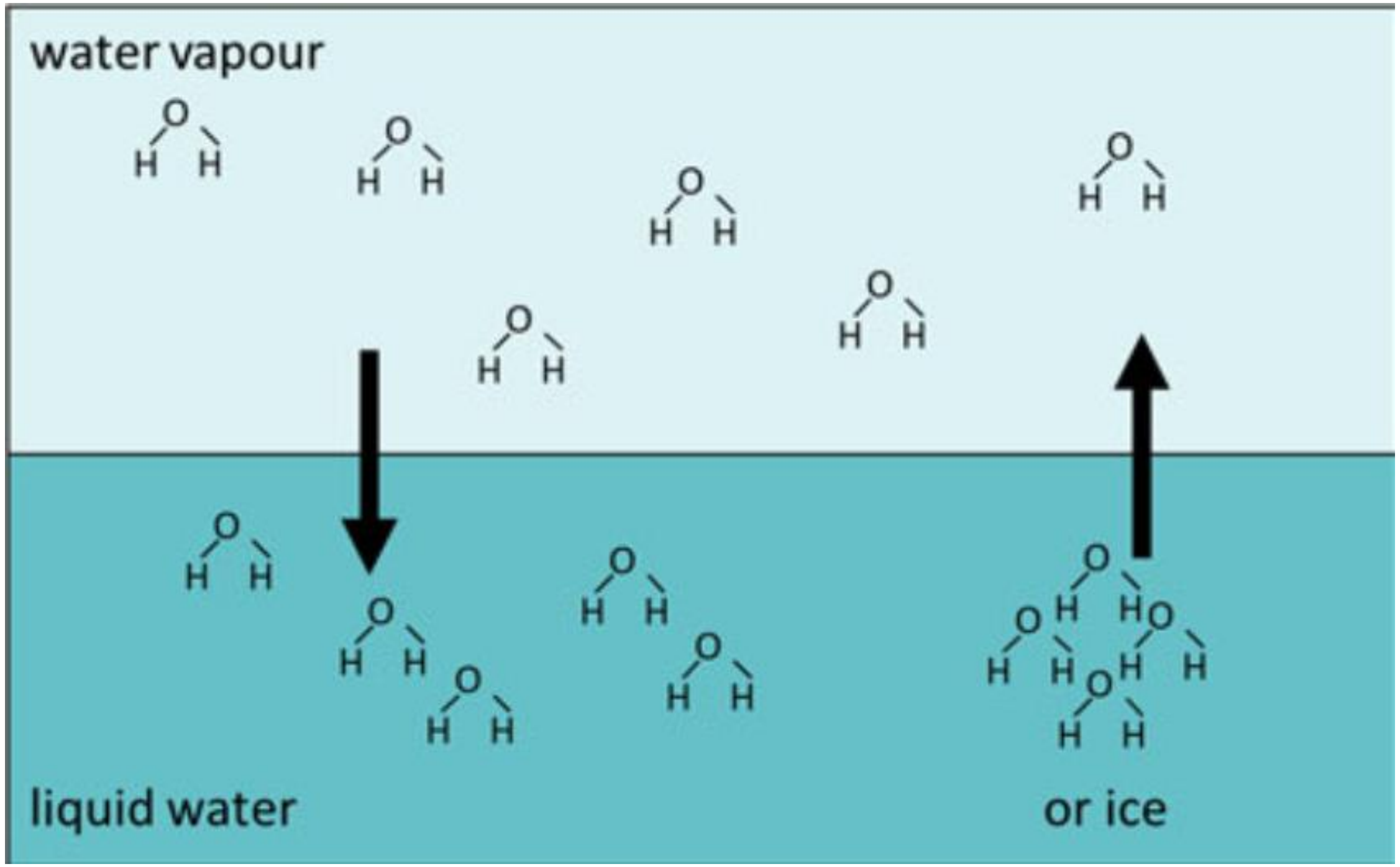
ETS = 0.55-0.85

ETS = 0.05-0.25

random forecast → ETS=0, perfect forecast → ETS=1

Addition: Relative humidity and ice supersaturation

- Thermodynamics
  - RH is the ratio of the partial pressure of water vapour e to its equilibrium pressure e^*
  - Saturation ⇔ dynamic equilibrium
  - RH: rel. to liquid water
  - RHi: rel. to ice
  - Saturation defines RH(i)=100%
  - Supersaturation: $e \geq e^*$
  - Triggers fluxes, which re-establish the equilibrium, once there are sinks for the fluxes.



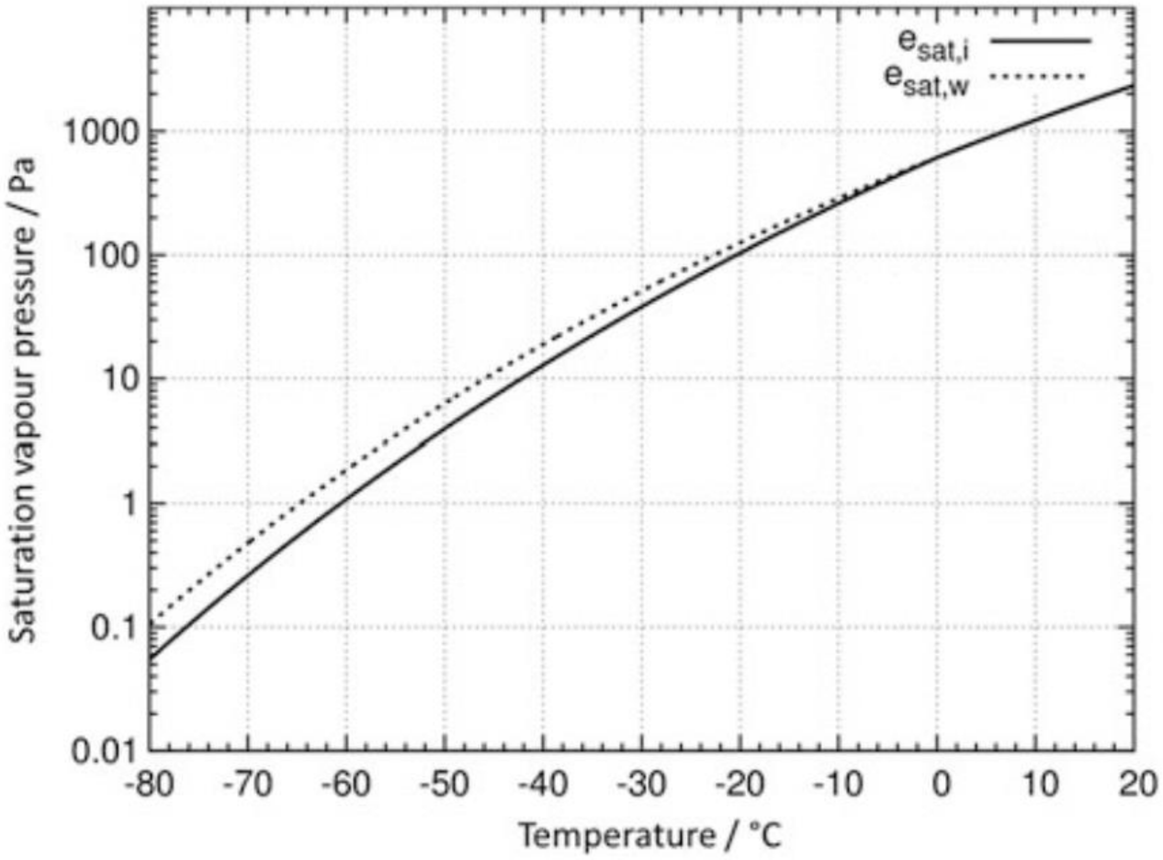
Some notes

- Relative humidity is a property of the water vapour, not of the air.
- It is the water vapour that is (super-, sub-) saturated, not the air.
- Air is not a sponge that could uptake water vapour; expressions like „water holding capacity of air“ or „the air is saturated with water“ are simply wrong, although such nonsense is even printed in textbooks.
- As long as air is an ideal gas, the other gas molecules have no influence on the partial pressure of the water molecules.
- Nothing in physics forbids supersaturation, but it is unstable and as soon there are appropriate sinks for water vapour, fluxes are triggered that lead back to equilibrium (saturation).

Relative humidity and ice supersaturation

- Thermodynamics and dynamics
  - Clausius-Clapeyron equations
    $$\frac{d \ln e^*}{d \ln T} = \frac{L}{RT} \quad \Rightarrow$$
  - Saturation pressure depends strongly on temperature T
  - RH(i) increases with decreasing T (and e^*).

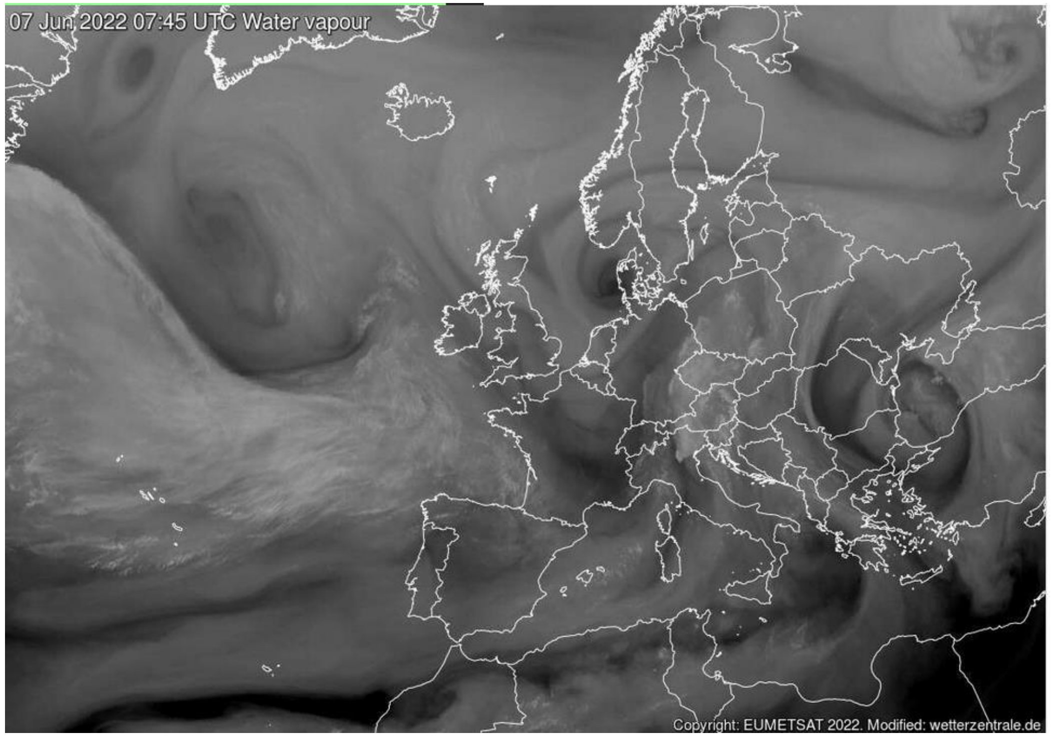
  - Vertical motions (uplifting of humid air) with adiabatic cooling is the main source of ice supersaturation.
  - Relative humidity and ice supersaturation are local quantities.



PREDICTION OF ISS

Properties of the water vapour field

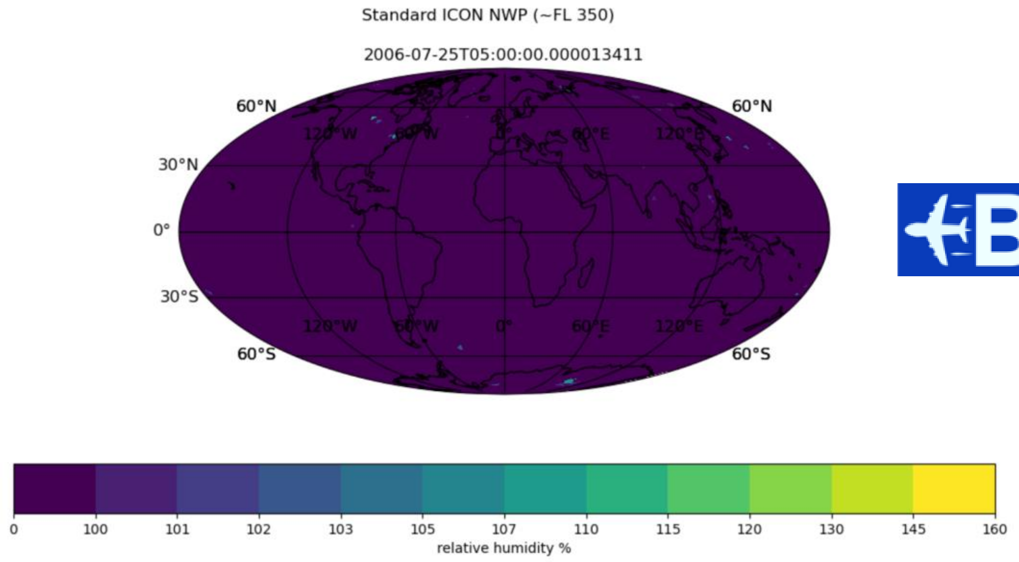
- Water substance comes in three phases and it is involved in cloud formation and decay;
- Water is involved in atmospheric chemistry (gases and aerosol);
- Relative humidity depends on absolute humidity and temperature – fluctuations of both impact RH(i);
- Thus, RH is a very inhomogeneous field with strong gradients;
- Supersaturation is an extremal state of the RHi field, more sensitive to q and T fluctuations/changes than average RHi in the bulk of its pdf;
- ISS or not-ISS is binary, that is, highly non-linear.

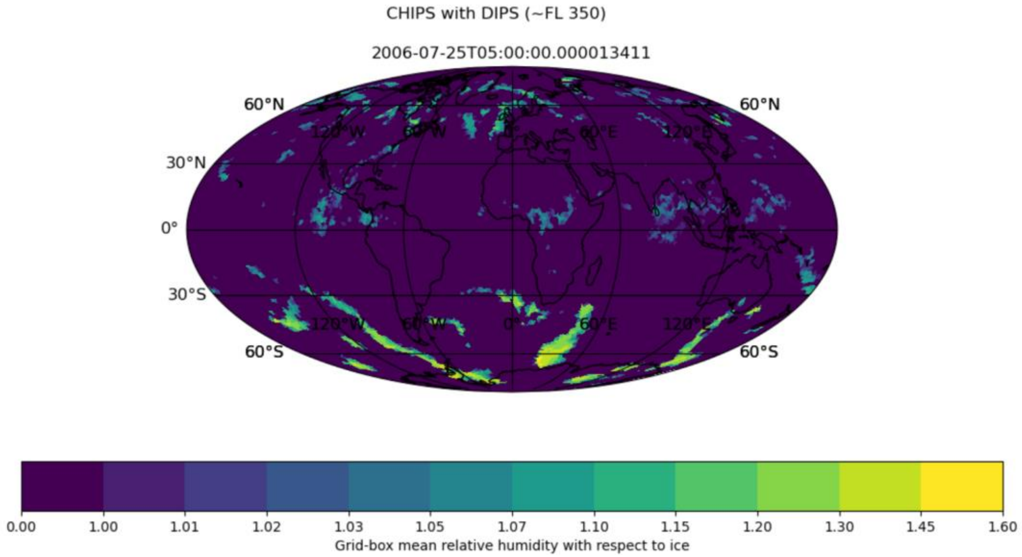


View of Europe and the Eastern Atlantic in the water vapour band of 6-7µm (EUMETSAT)

Outdated formulation of cloud physics in weather forecast models

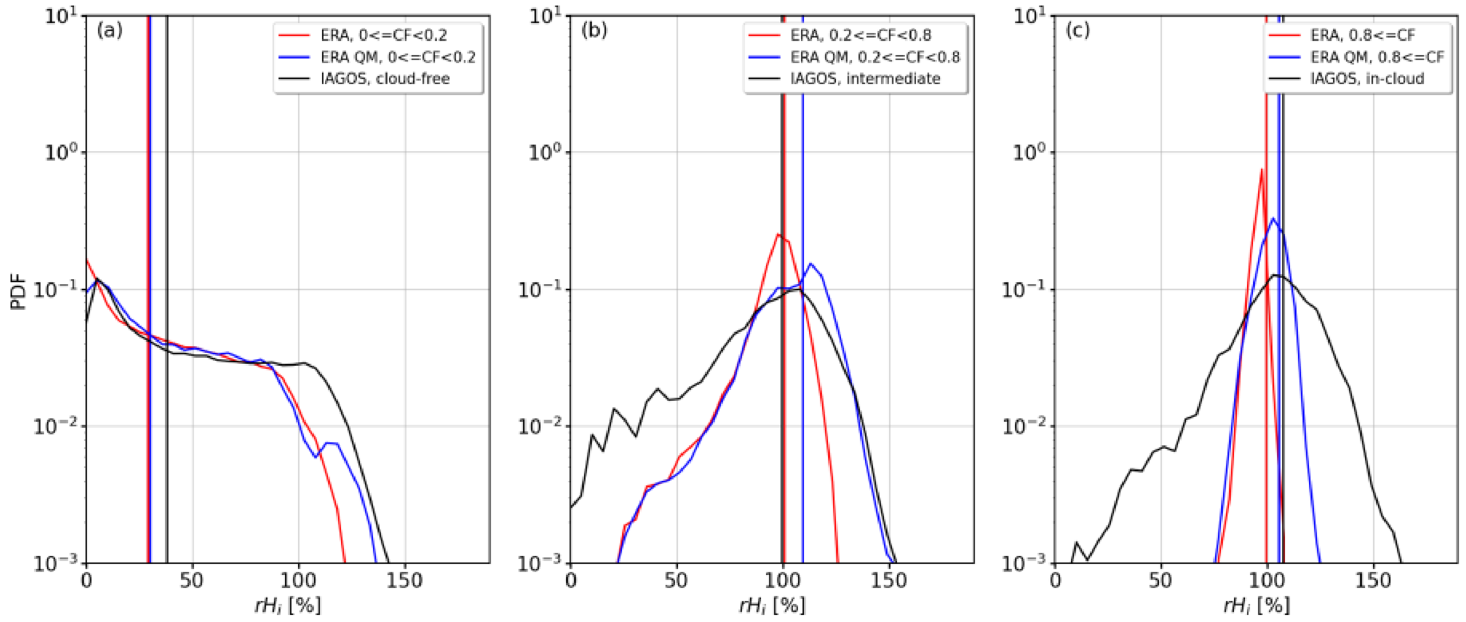
- Upper troposphere and ISS not in focus of NWP;
- NWP runs are time critical;
- Simple formulation of cloud physics in NWP models;
- Little RH data of the UT for data assimilation;
- Formulations of cloud parameterisations that abandon traditional simplifications yield better results.





Sperber, Dissertation

Unphysical (conditioned) pdfs of RHi

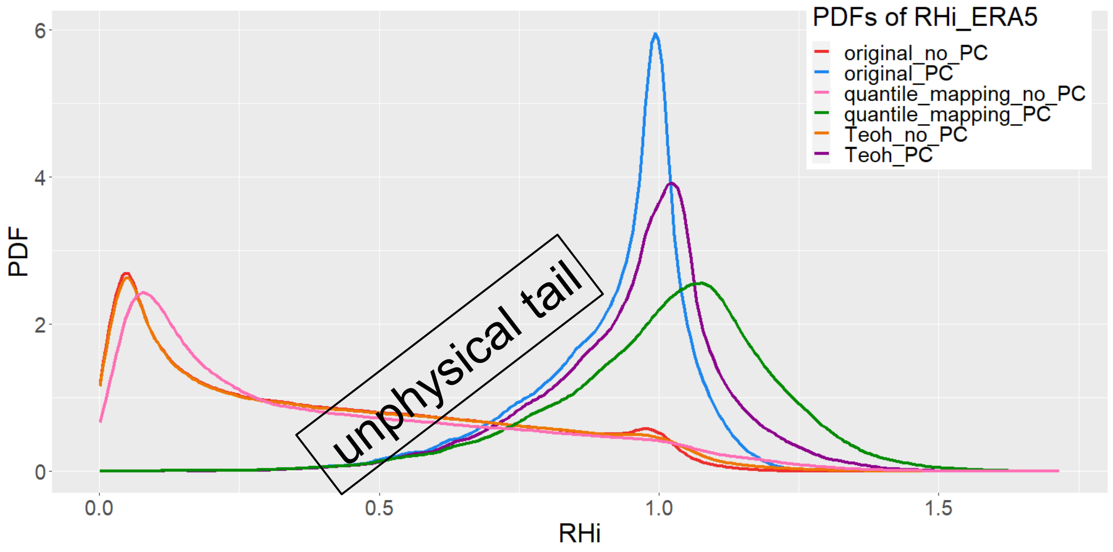


unconditioned pdfs:
black: IAGOS reference
red: ERA5
blue: corrected ERA5

Wolf et al. 2025.

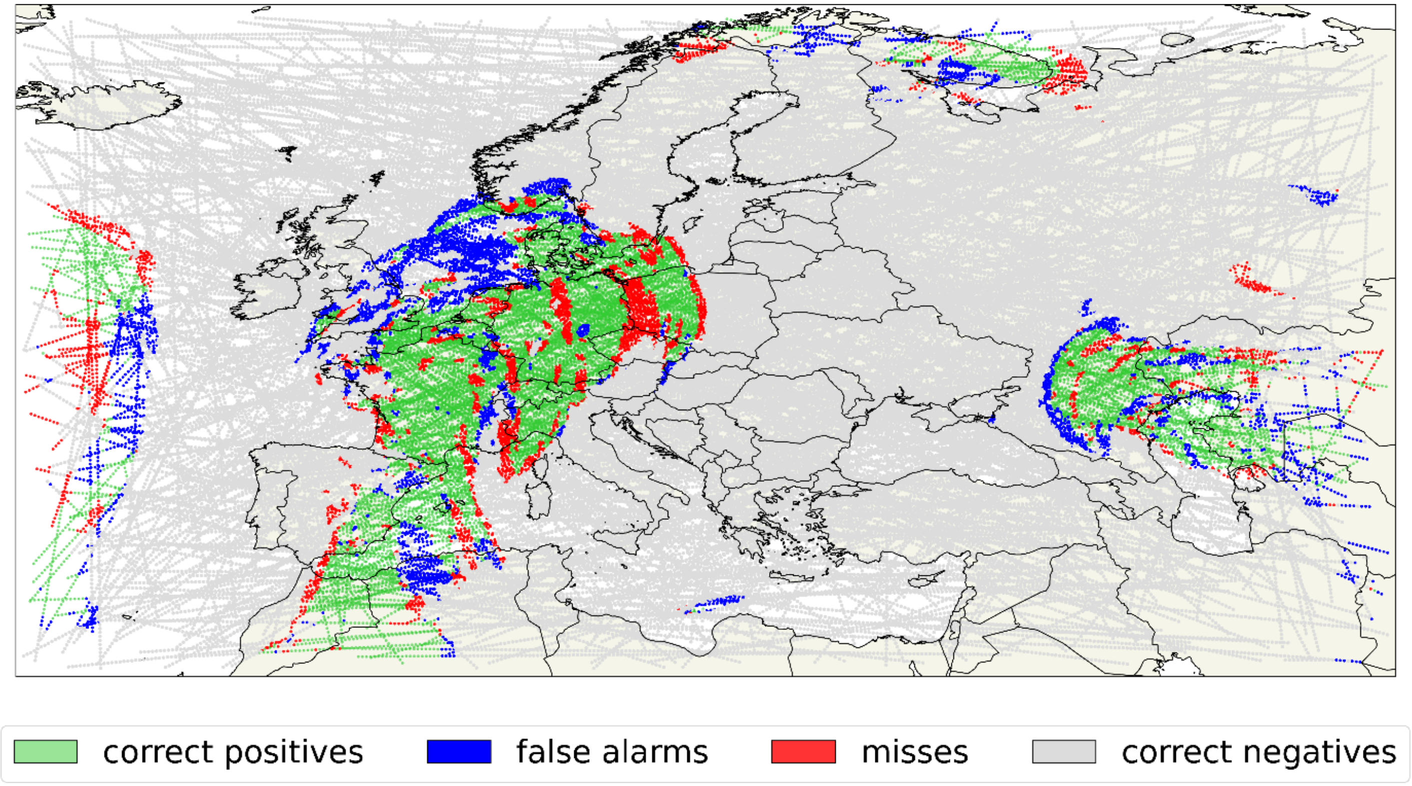
ERA5 RHi pdfs conditioned on
non-ISS (reddish) and
ISS (blue and green),
original and after corrections

Hofer et al. 2024.



Nonlinearity of atmospheric dynamics

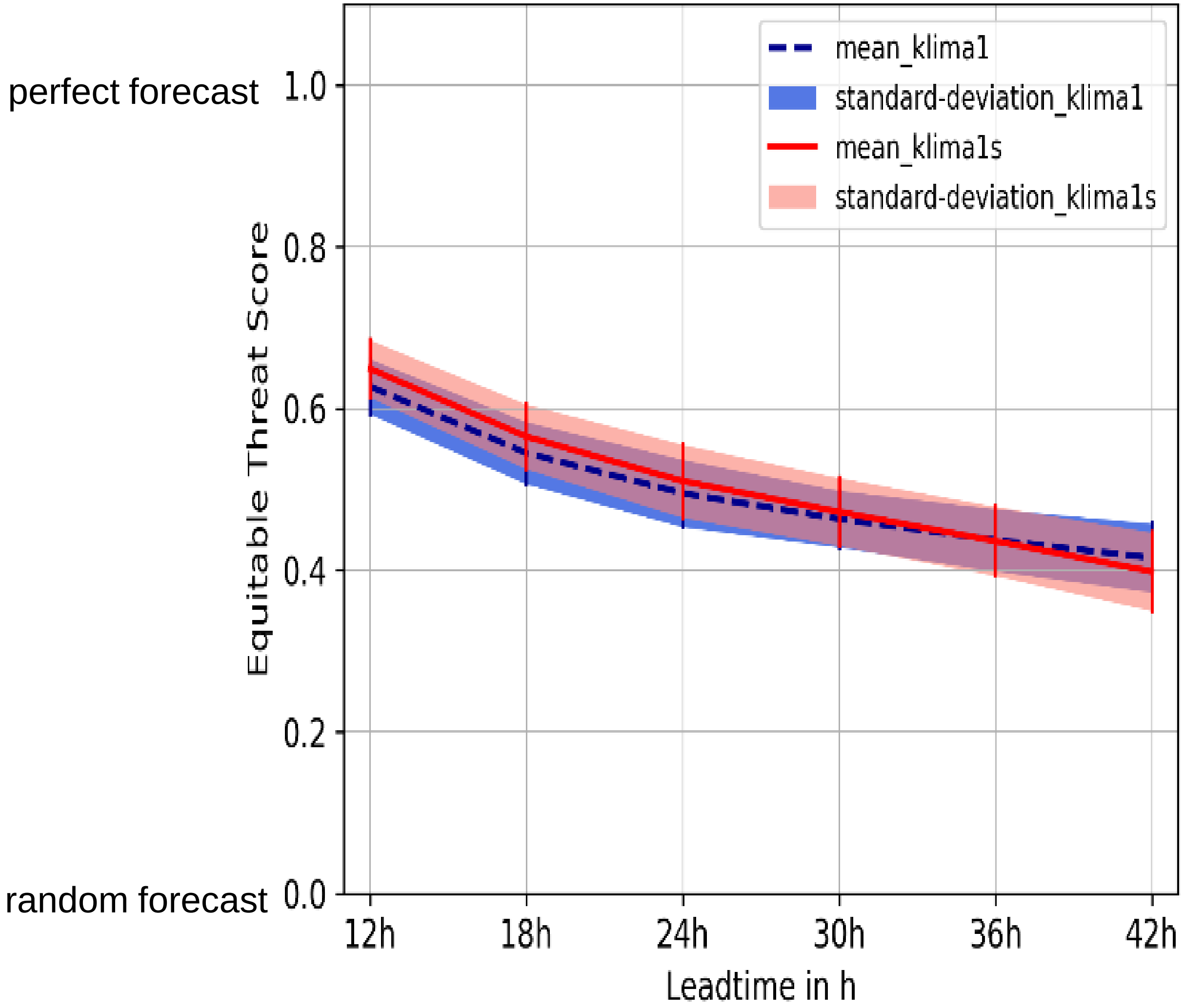
- Forecast of ISS at flight planning compared to the most recent forecast at flight time yields
  - Correct forecasts of ISS (correct positives),
  - Correct forecasts of non-ISS (correct negatives),
  - False alarms,
  - Misses;
- The frequency of these 4 possibilities can be expressed via ETS.



von Bonhorst et al., MetZ 2025

Forecast stability

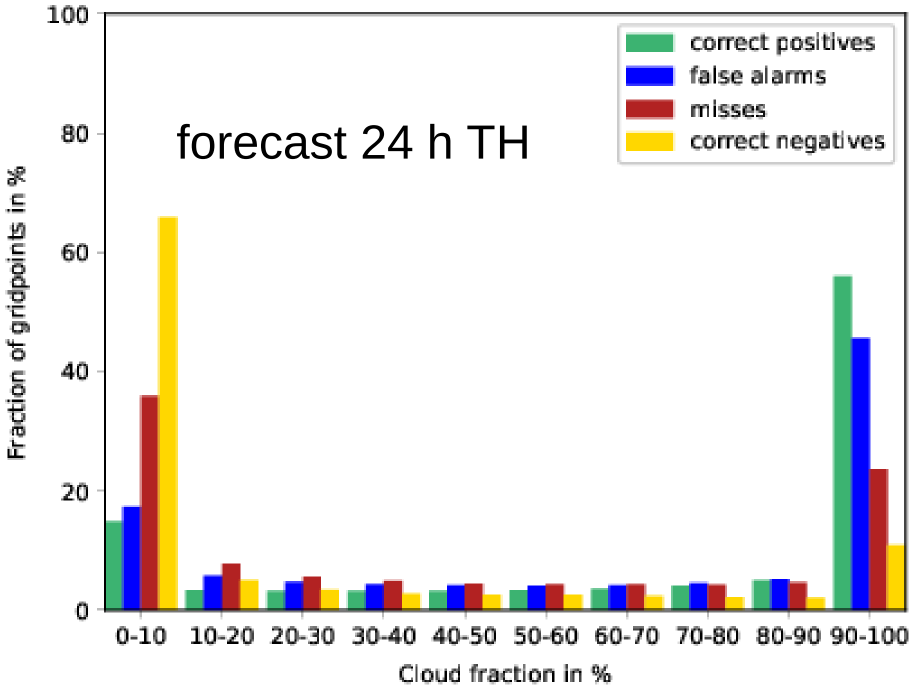
- General problem of forecast stability, independent of the formulation of cloud physics in the NWP model

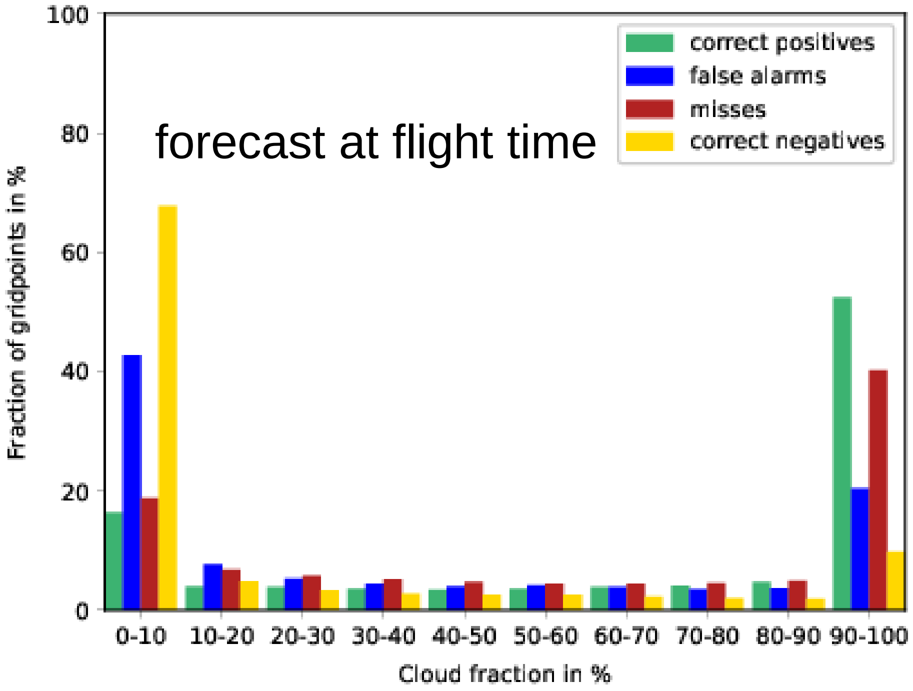


von Bonhorst et al., MetZ 2025

Contrail prediction and natural cirrus clouds

- Natural cirrus prediction has correct forecasts, false alarms and misses parallel to contrail prediction.
- Natural cirrus thus dampens the system: correct contrail forecasts are less beneficial, wrong forecasts less damaging in cloudy than clear skies.



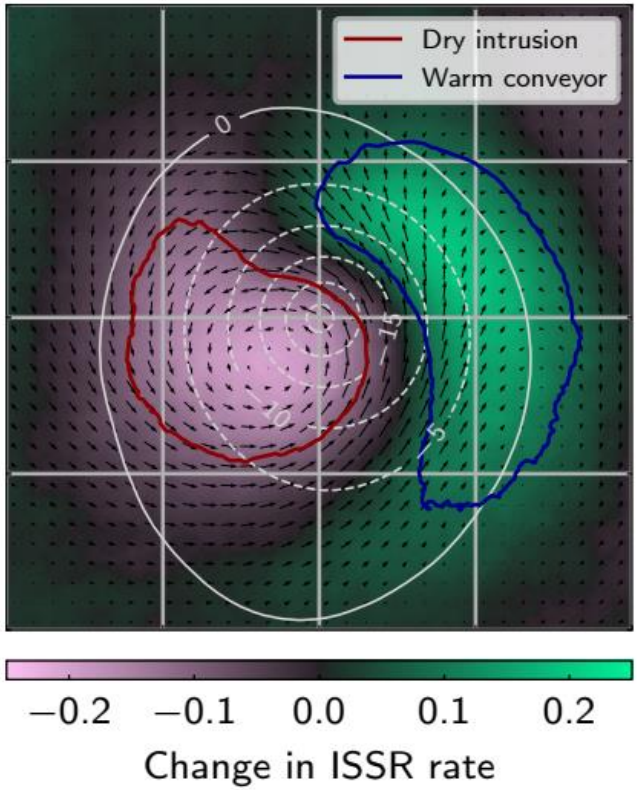


von Bonhorst et al., MetZ 2025

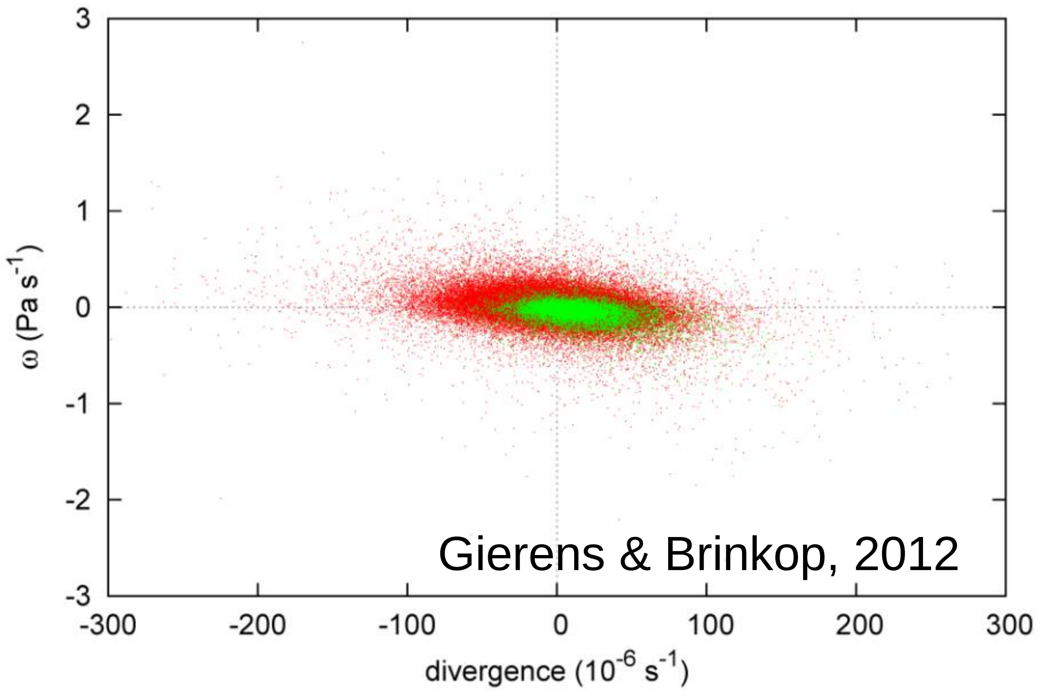
DYNAMICAL PROXIES

Dynamical fields and ISS

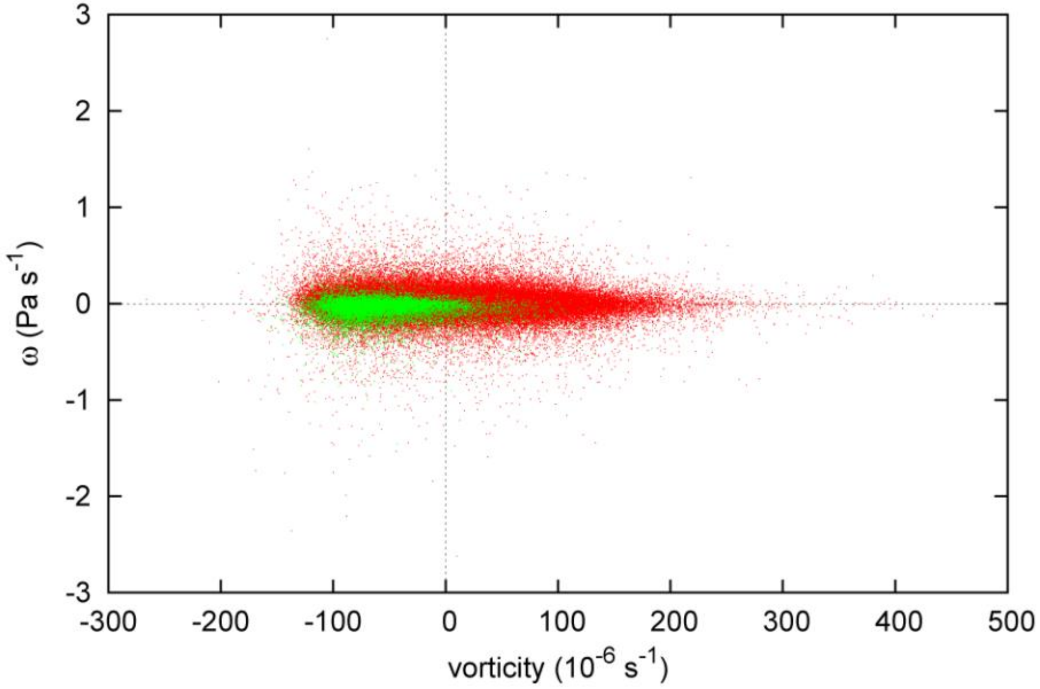
- ISS prefers certain dynamical regimes and avoids others.
- However, there is always strong overlap in the conditioned pdfs.



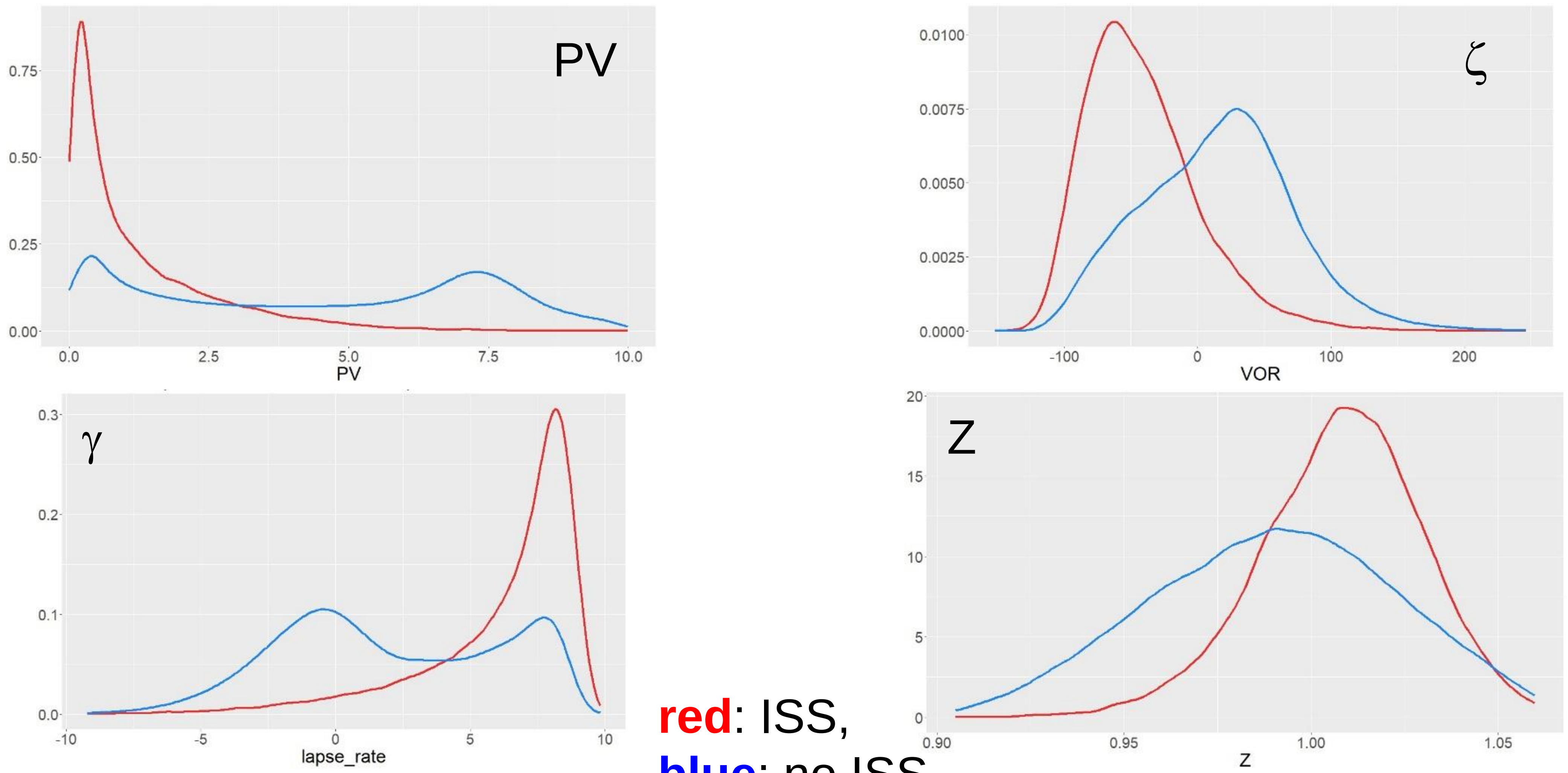
Driver et al., preprint, 2025



Gierens & Brinkop, 2012



Distinct conditional distributions of dynamical fields



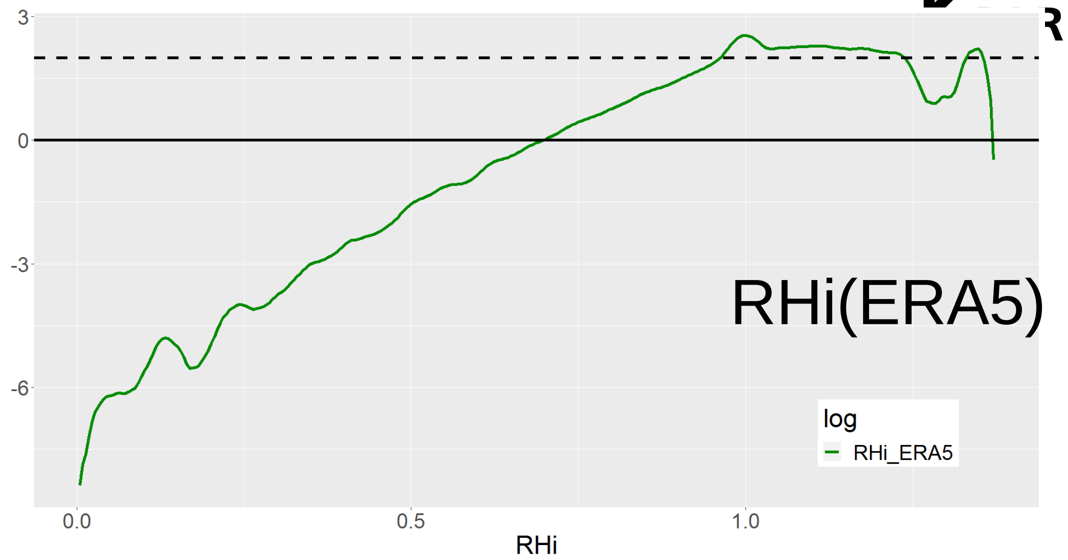
red: ISS,
blue: no ISS

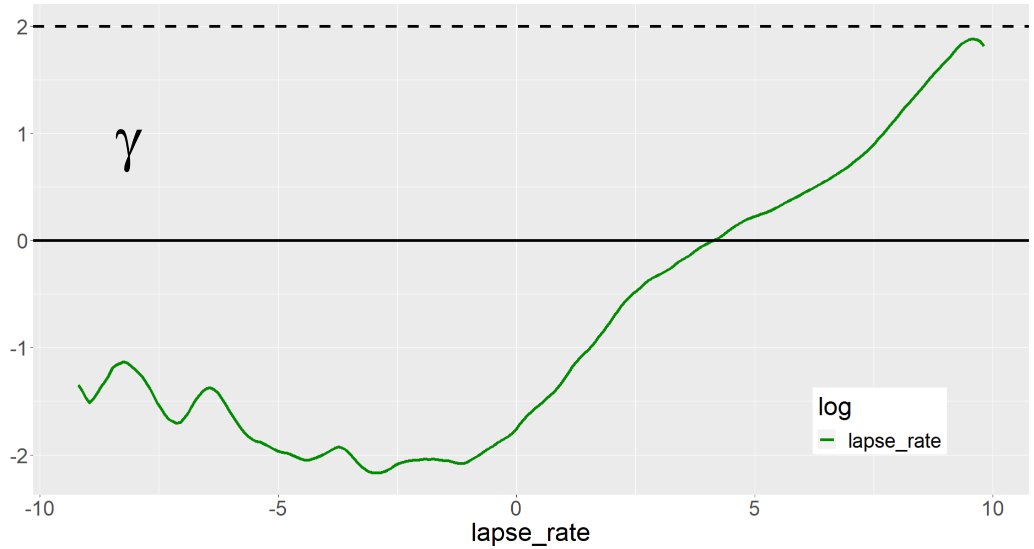
Wilhelm et al., 2022

Use of proxies in Bayesian learning

- $\log(\Omega|x) = \log\Lambda(x) + \log\Pi$
- with *a posteriori* and *a priori* odds ratios Ω, Π and
- likelihood ratio Λ
- $(\Omega|x) = P(ISS|x)/P(\overline{ISS}|x)$
- $\Lambda(x) = f_X(x|ISS)/f_X(x|\overline{ISS})$
- $\Pi = P(ISS)/P(\overline{ISS}) = 12.5/87.5, \log\Pi \approx -2$

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



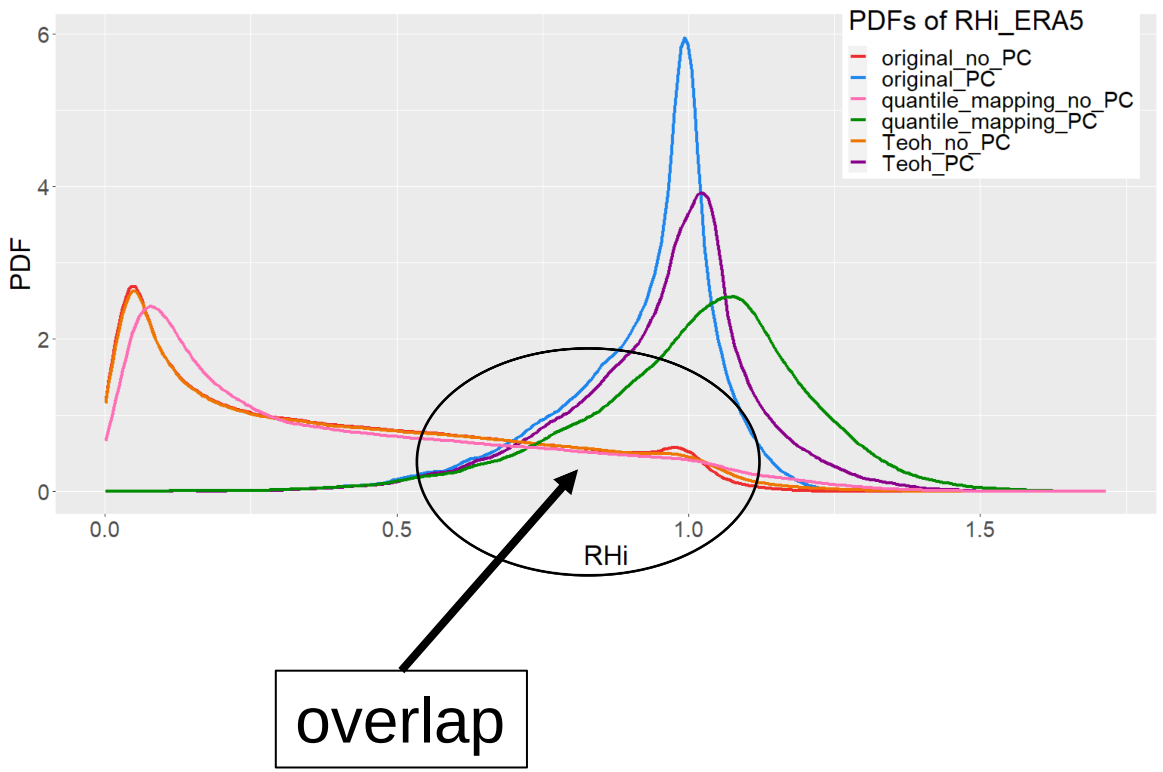


Hofer et al., 2024

Regression using generalised additive models (GAMs)

- GAM: $\log(\Omega|x) = \beta_0 + \sum f_i(X_i)$

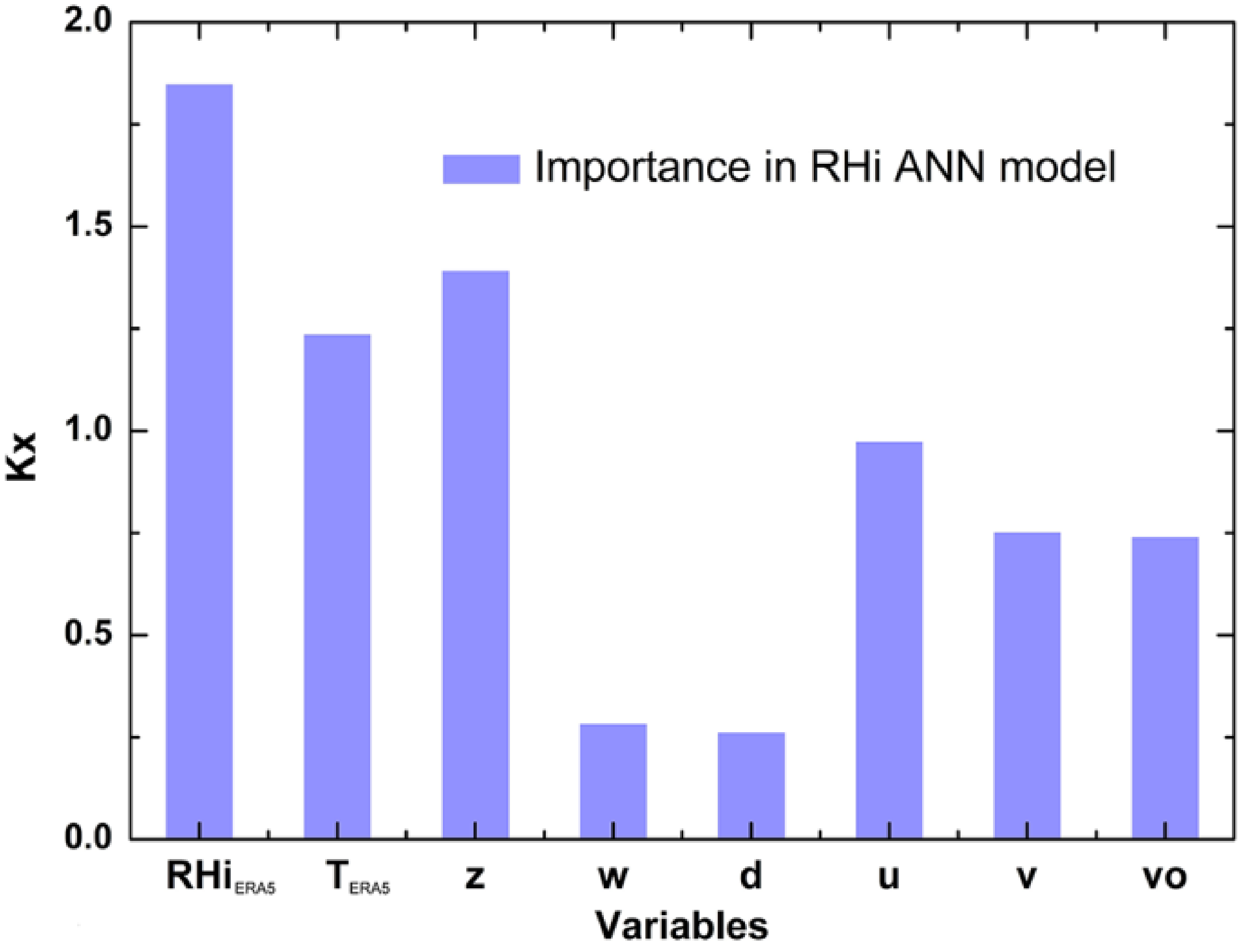
- inclusion of RHi(ERA5) is essential
- ETS values do not get larger than about 0.38
- inclusion of proxies does not raise ETS significantly
- a priori correction of RHi does not help
- better results are prohibited by the large overlap btw. the cond. pdfs



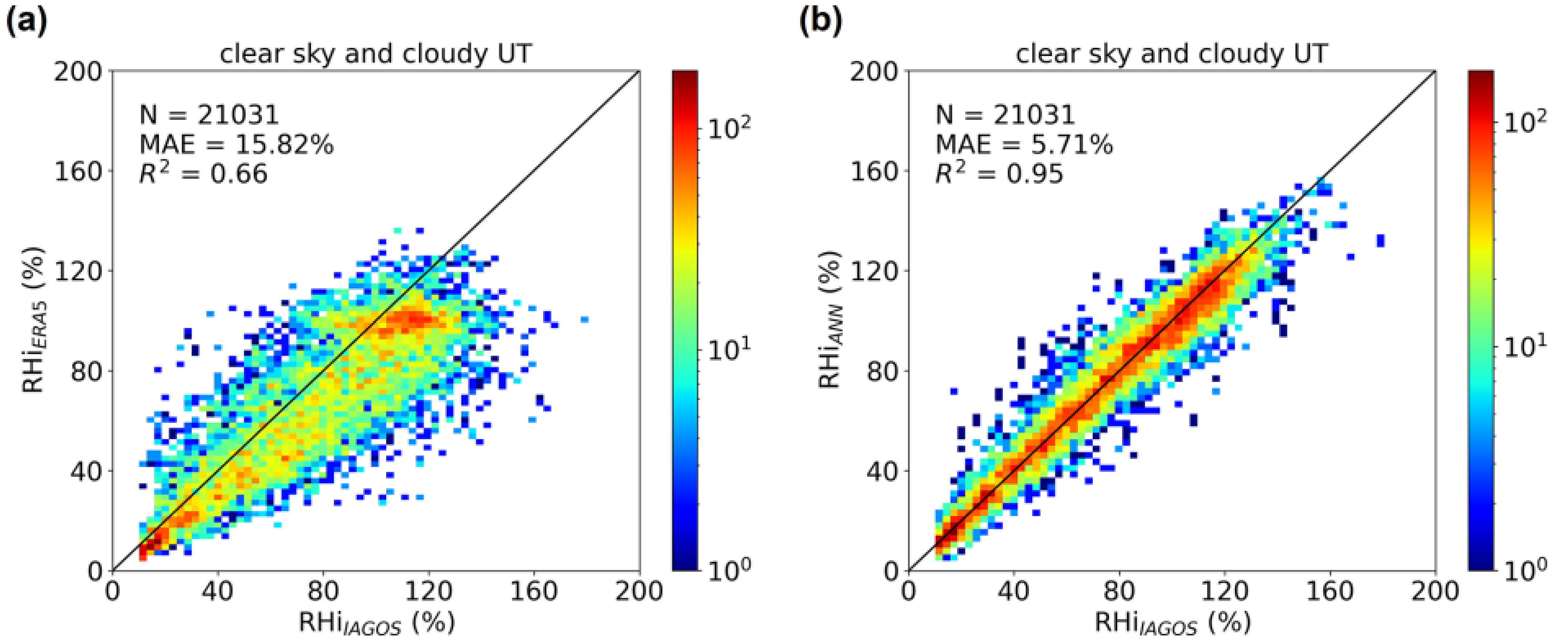
Hofer et al., 2024

Use of more ambient information (time and space) in ANN

- Ziming Wang et al. (2025) use more dynamical fields, incl. horizontal wind components u and v,
- and use a larger environment around any point (±2 pressure levels)
- and -6h and -2h forecasts as well
- to train an ANN
- inclusion of RHi(ERA5) is again essential
- u, v have more effect than w, d



Higher effort gives better results



NOVEL MICROPHYSICS MODULES

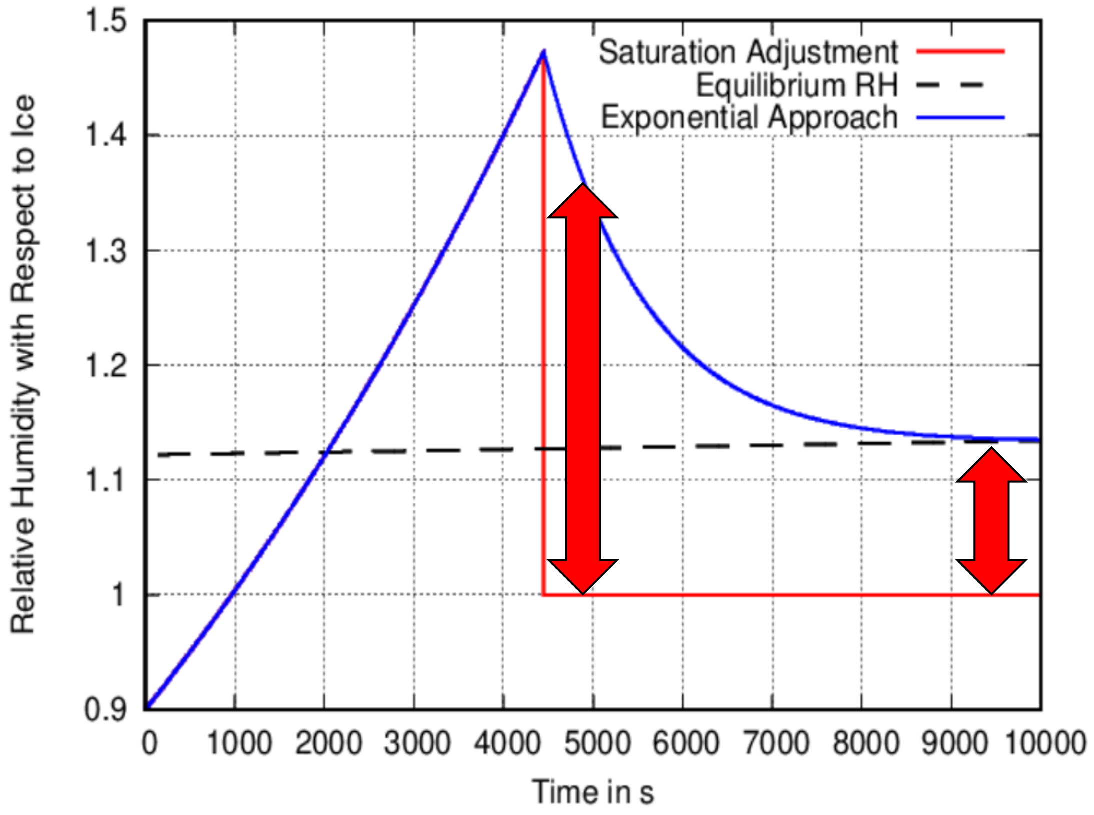
Problems with current one-moment schemes

- In order to keep CPU time for μφ calculations short, NWP models traditionally use one-moment μφ, i.e. only the condensate mass in a grid box is a prognostic quantity.
- Clouds form as soon as saturation is reached which inhibits ISS to build up,
- or clouds form at a critical supersaturation, followed by saturation adjustment (fast μφ), that is, supersaturation only occurs in clear sky.
- Possible but CPU-expensive solution: two-moment scheme

- In BeCoM we try something in between: a one-moment scheme with cloud formation at a critical supersaturation and slow μφ (no sat. adjustment).

Concept for a slow μφ cloud scheme

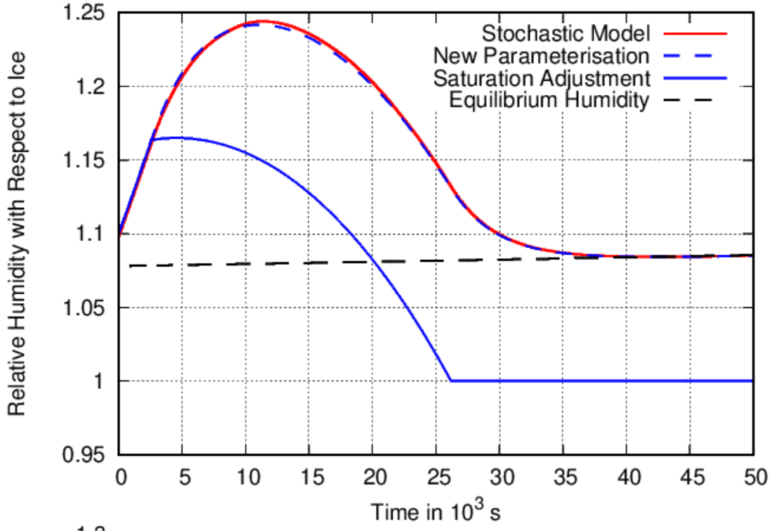
- Sub-grid variability in the humidity field (depending on grid size)
- Whenever the humidity threshold for homogeneous nucleation is passed locally within a grid box, the resulting cloud fraction is predicted
- Exponential decay of specific humidity assumed in the cloudy part of the grid box instead of instantaneous conversion of all supersaturation to ice (saturation adjustment)

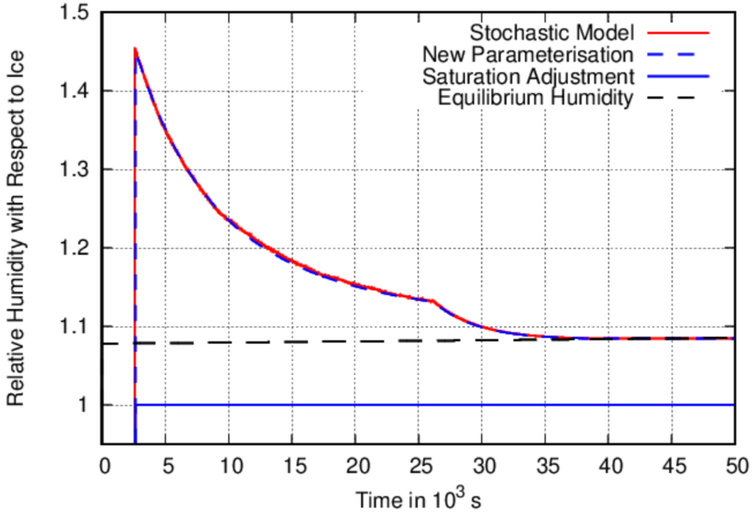


Application examples

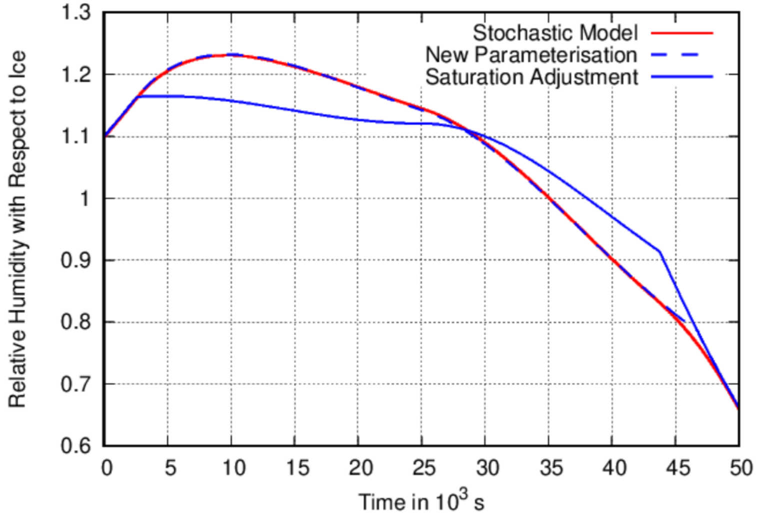
Grid mean relative humidity

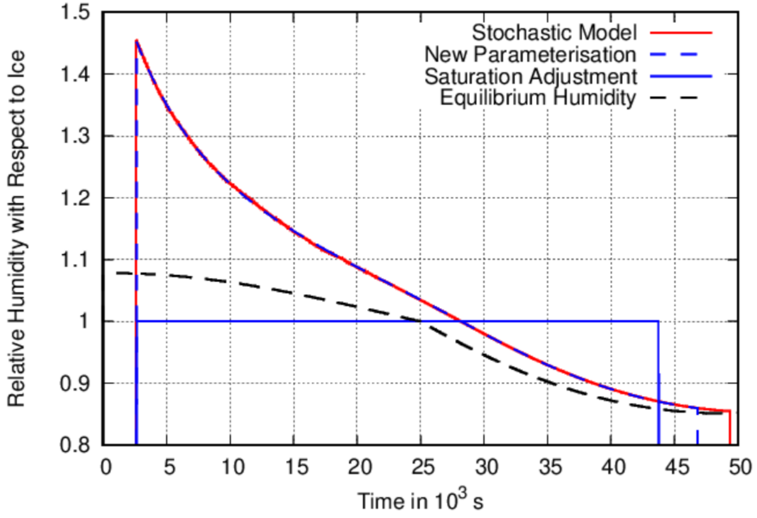
In-cloud mean relative humidity





slow uplift
2 cm/s





slow uplift,
followed by
subsidence

Sperber and Gierens, 2023

PARTIAL CONTRAIL AVOIDANCE

Motivation and scientific questions

- How large is the climate benefit (utility) if a few out of many contrails in the same region of the sky are avoided?
  - How behaves the utility of contrail avoidance when many contrails are around and overlap?
  - What does this imply for the calculation of the climate benefit of avoided contrails?
- Examples:
  - Commercial services that serve one or a few airlines,
  - Avoidance experiments conducted by single airlines.

Approach: simple mathematical model

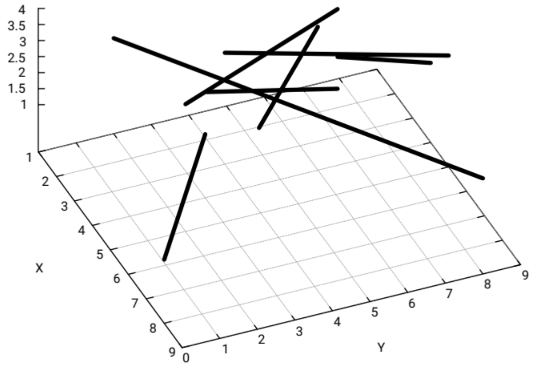
- In order to answer the questions I use a simple mathematical model, i.e.
  - a number of simple assumptions leading to
  - a number of simple equations that lead to the formulation of a utility function.
- Analysis of the utility function provides insight into
  - principle (qualitative) behaviour
  - no detailed quantitative results.
- For quantitative results, numerical models are required that treat contrails individually, but as interacting and overlapping objects, plus radiation.
  - Many different situations needed to provide insight into general rules;
  - I expect that the general rules obtained from the mathematical model are reproduced by and large by runs of numerical models.

Effective contrail coverage for overlapping contrails

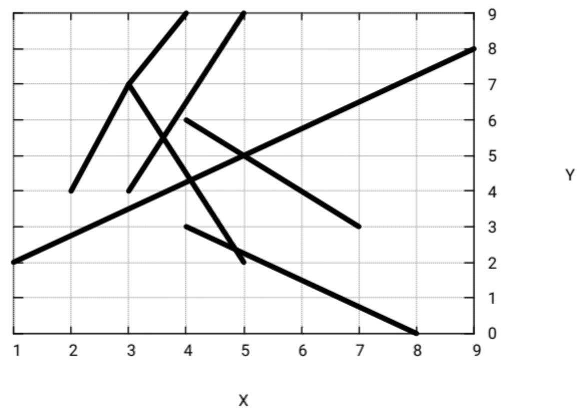
- The presence of contrails blocks infrared radiation from escaping to space.
  - Geometrical coverage b_{geom}
  - Transmission $e^{-\tau}$, that is a fraction $0 \leq (1 - e^{-\tau}) \leq 1$ of infrared photons cannot escape to space and deliver their energy into the atmosphere.
  - Both quantities are combined to an effective coverage $b = b_{geom}(1 - e^{-\tau})$.

- If there are many (N) contrails overlapping in a random fashion, then the total effective coverage can be written as

$$B = 1 - (1 - b)^N = B_{geom}\left(1 - T_{eff}\right)$$



3-D situation, relevant for μφ and individual properties



2-D projection, relevant for radiative transfer

Formulation of the utility model

- Assumption: scene-individual (instantaneous) climate effect $E = E(B|\boldsymbol{X})$
  - $\boldsymbol{X}$: vector of actual weather and traffic parameters,
  - assumption: $\boldsymbol{X}$ varies slowly and can be considered constant for a while
  - then $E = E(B)$ alone, in the simplest way: $E = \alpha B^{\beta}$; $\alpha = \alpha(\boldsymbol{X}), \beta = \beta(\boldsymbol{X})$

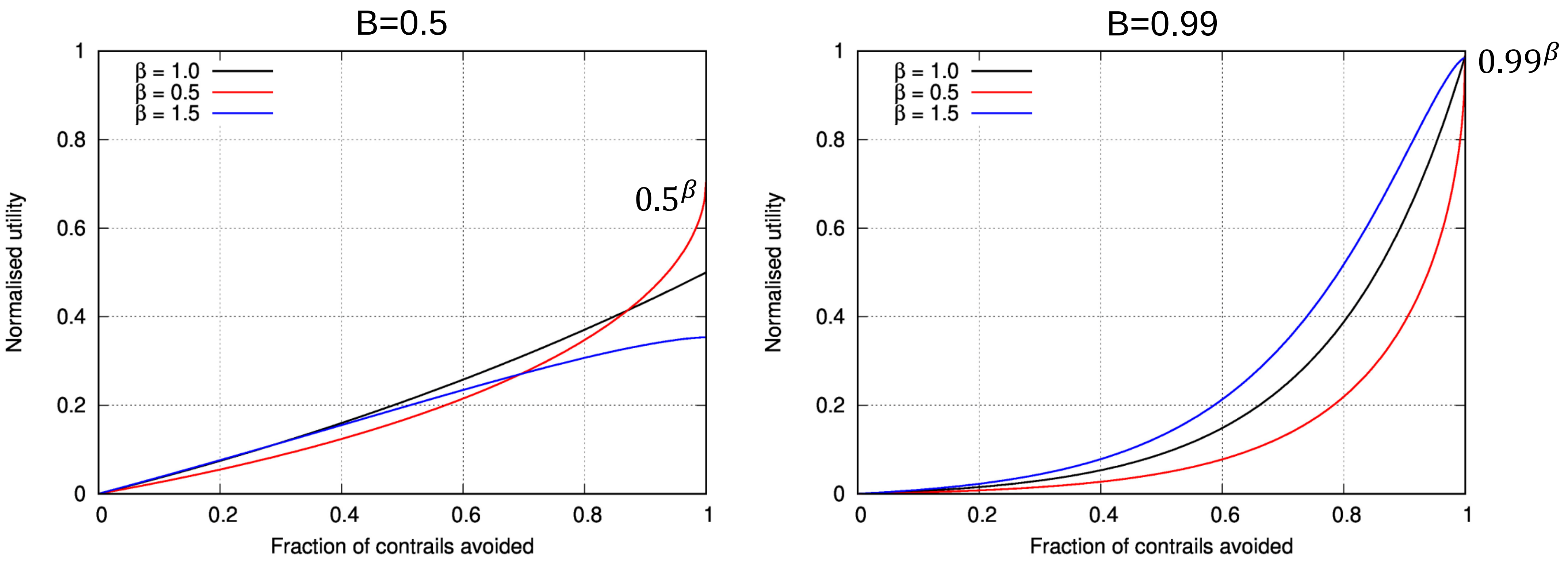
- Utility definition: $U = \alpha B^{\beta} - \alpha B'^{\beta}; B > B'$
- Avoidance of a fraction $\mathrm{M}/N; M \leq N$ of the contrails has the following utility:

$$U\left(\frac{M}{N}\middle|\alpha, \beta, B\right) = \alpha\left\{B^{\beta} - \left[1 - (1 - B)^{\left(1 - \frac{M}{N}\right)}\right]^{\beta}\right\}$$

- Normalised utility U/α. α is the maximum utility in a given scene. $\beta \approx 1$.

- Avoidance of all contrails $\rightarrow U/\alpha = B^{\beta}$.

Simple examples: normalised Util. vs. fraction avoided

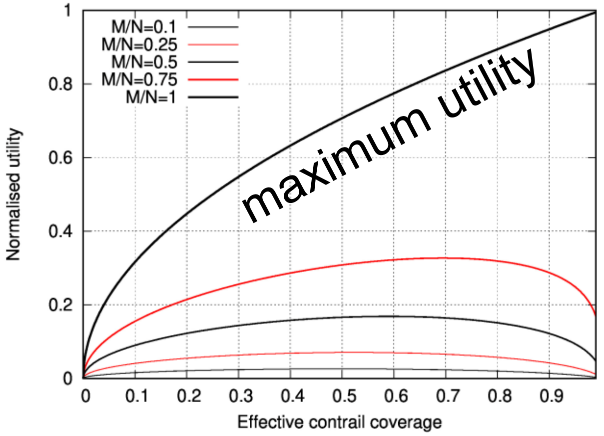


mildly non-linear shape

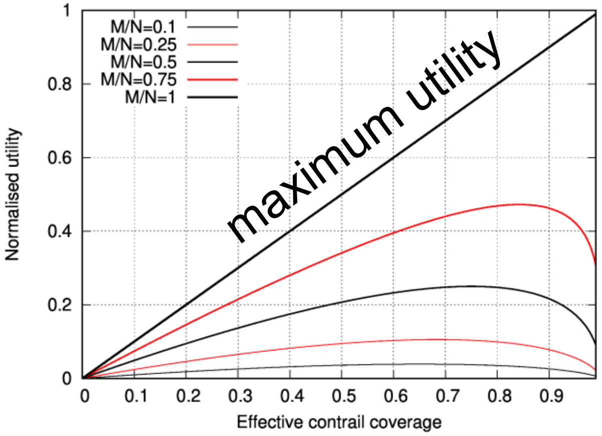
strongly non-linear shape

Util. and relative util. vs. effective contrail coverage

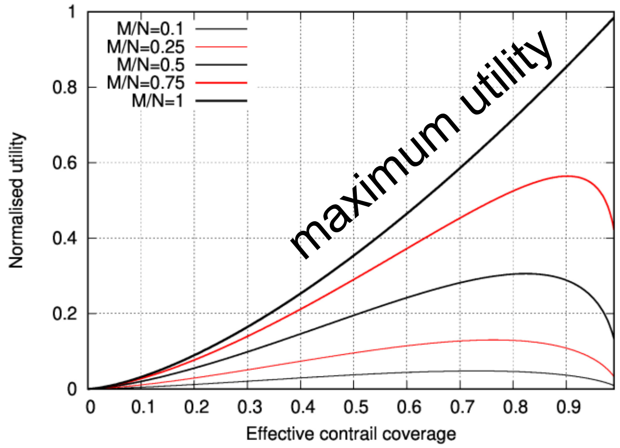
β=0.5



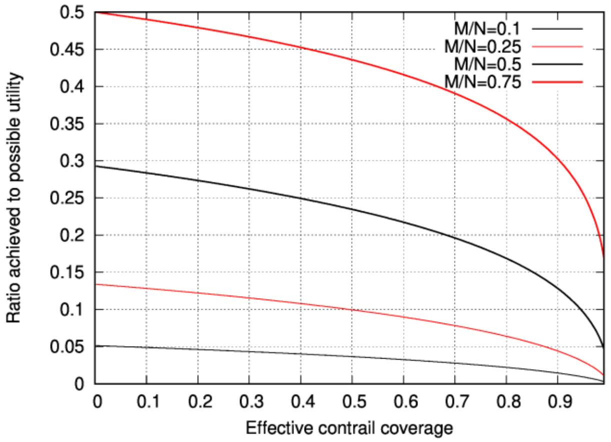
β=1.0

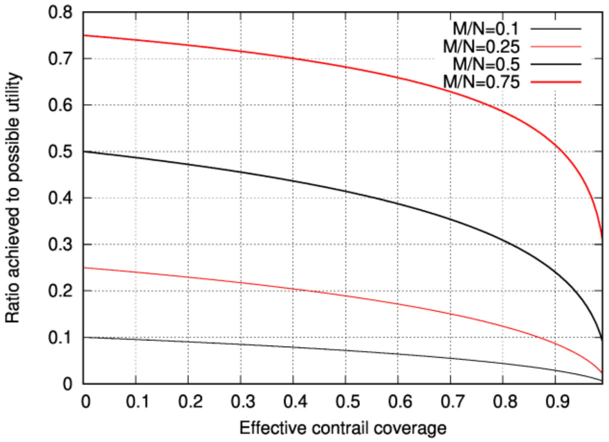


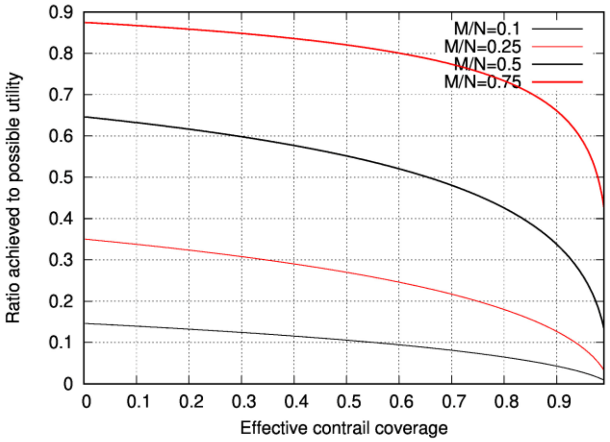
β=1.5



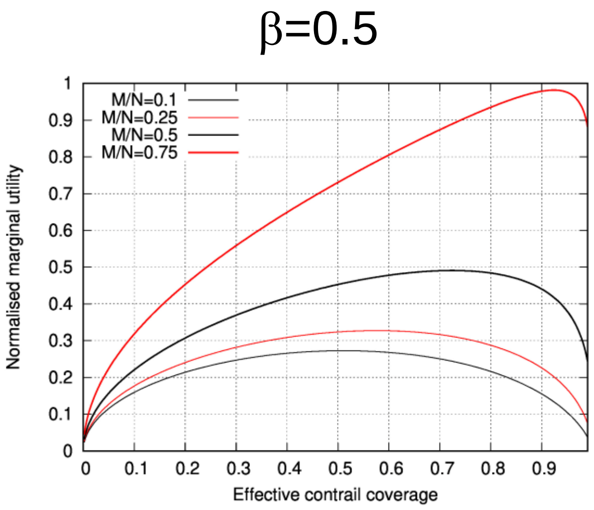
Ratios of achieved to maximum possible utility

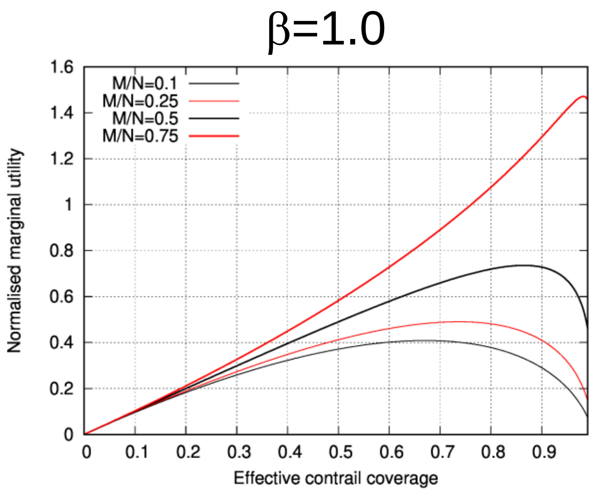


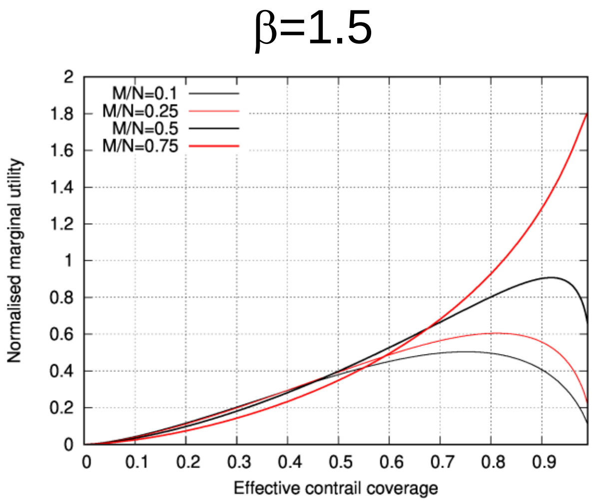




Marginal utility: Utility of avoiding one more contrail







- Marginal utility: first derivative wrt M/N of the (normalised) utility function: $\frac{d(U/\alpha)}{d(M/N)}$
- M.U. is always positive. Avoiding one more contrail increases the utility.
- However, as the necessary rerouting generally requires more fuel $\rightarrow$ higher emissions, the marginal utility must exceed the marginal climate cost (damage), expressed in the same units as the utility.
- Simple assumption for climate cost: $\frac{C}{\alpha} = \kappa B \frac{M}{N}$ (that is, cost is proportional to avoided fraction).
- Marginal utility must exceed marginal cost, that is $\kappa B < \frac{d(U/\alpha)}{d(M/N)}$.

SUMMARY AND CONCLUSIONS

Summary and conclusions

- Contrails contribute significantly to radiation and climate impacts of aviation,
- In principle this negative impact can be avoided by not flying in ISSRs,
- Forecast of contrail formation is relatively reliable (SAC),
- Forecast of ice supersaturation is currently challenging,
- Use of dynamical proxies (at location and time of the flight) in modern regression methods improves the forecast not sufficiently, but with extended information (past situation and larger environment of flight location) in an ANN better results are achieved,
- NWP models need $\mu\varphi$ schemes that represent ISS (2-moments or slow $\mu\varphi$),
- Humidity measurements at flight altitudes for data assimilation helps to constrain modelled humidity fields.
- Contrail avoidance should try to avoid a large fraction of contrails; the utility of avoiding one contrail depends on the coverage of all contrails.