Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Operation Hydrometeors
–
An efficient volume scan polarimetric radar forward OPERAtor
to improve the representaTION of HYDROMETEORS
in the COSMO/ICON model

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Outline

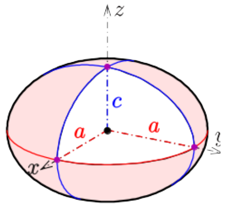
- Polarimetric forward operator: Status summary
- Model evaluation: ICON-D2
- Outlook

Polarimetric forward operator: Status summary

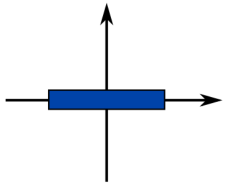
- Approach: add polarimetry to EMVORADO, but **keep existing features & characteristics**
  - **consistent model coupling, sensor (network) modelling**
  - hydrometeor property assumptions
  - **speed**
- Added scattering model option: T-Matrix + angular moments
  - shape (AR), orientation (σ_β), melt fraction dependence from Ryzhkov et al. (2011)

individually featured by other PFOs, too, but **unique in combining** them into one operator

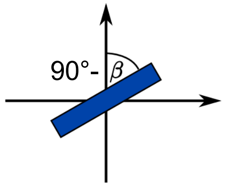
liquid	rain	ice	snow	graupel, hail	
Rayleigh	oblate spheroids	oblate spheroids	oblate spheroids	oblate spheroids	shape
-	Brandes (2002) f(deg4-in-D)	Matrosov (1996) thick plates aD^b	1.0-0.02*D 0.8 (D>10mm)	1.0-0.02*D 0.8 (D>10mm)	AR
-	10°	10°	40°	40°	σ_β
-	-	both: lin. in f_m to rain	both: lin in f_m to rain	AR: lin. in f_m between $AR_{wet}=[AR_{dry},0.8,0.48,AR_{rain}]$ for $f_m=[0,0.2,0.8,1]$ σ: lin. in f_m to rain	melting behaviour (f_m=mass melt fraction)



Basic orientation



Tilted orientation



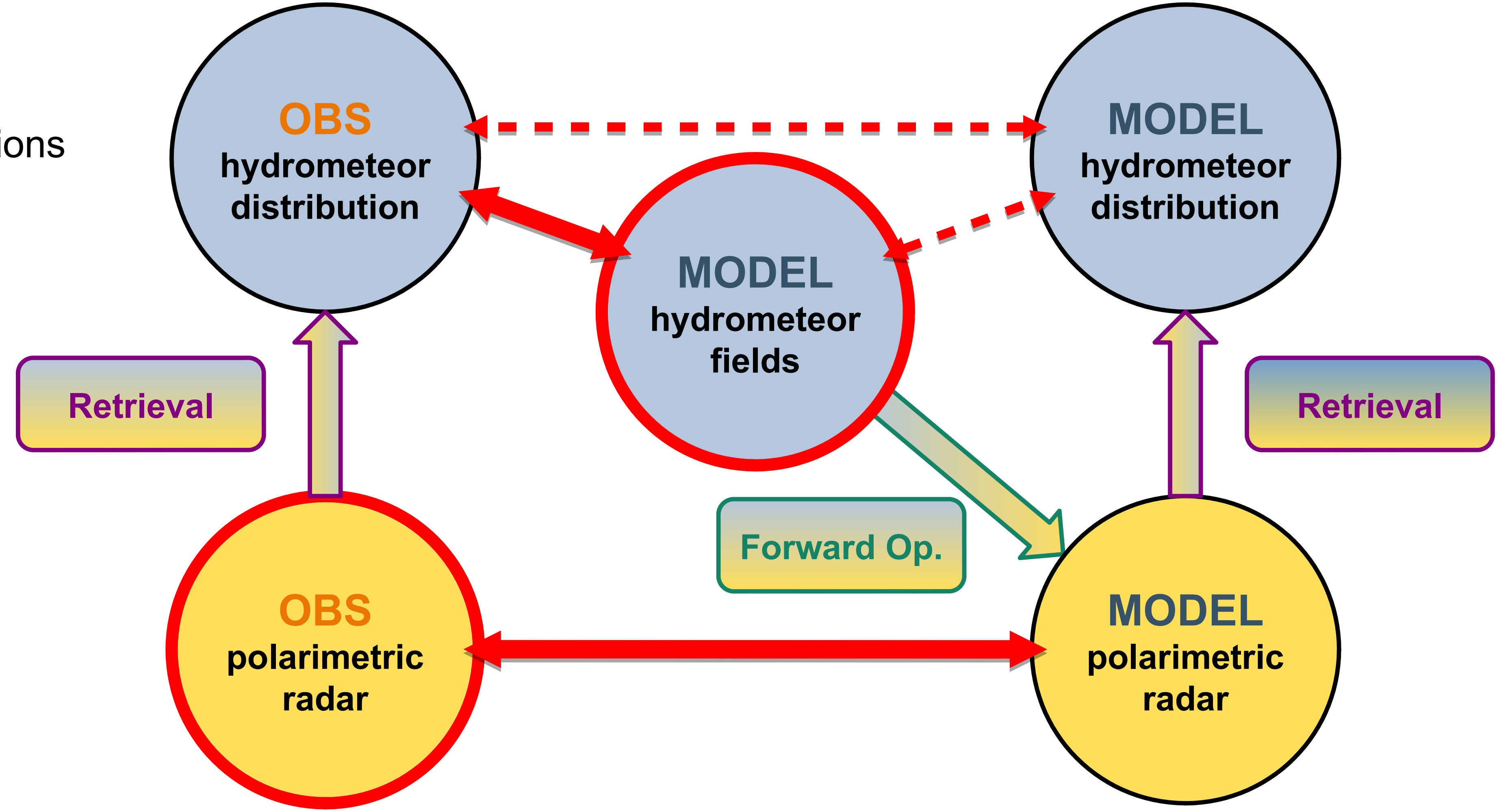
Polarimetric forward operator: Recent developments (22/02~)

- ➔ Licensing cleared up & settled
  - details see extra slides
- ➔ Improved portability & usability
  - portable bulk scattering lookup tables
  - mixing of existing & virtual radar stations
  - obs data from further countries (OPERA hdf5; Switzerland, Belgium, France, Denmark, Netherlands, Poland, Czech Rep.)
  - apply DA increments offline
- ➔ Installing & running in a Virtual Machine (work in progress)
  - outside the DWD „habitat“
  - ERAD short course triggered

Model evaluation: Method

➔ Dual strategy (→ Pejcic): Compare in model and in observation space

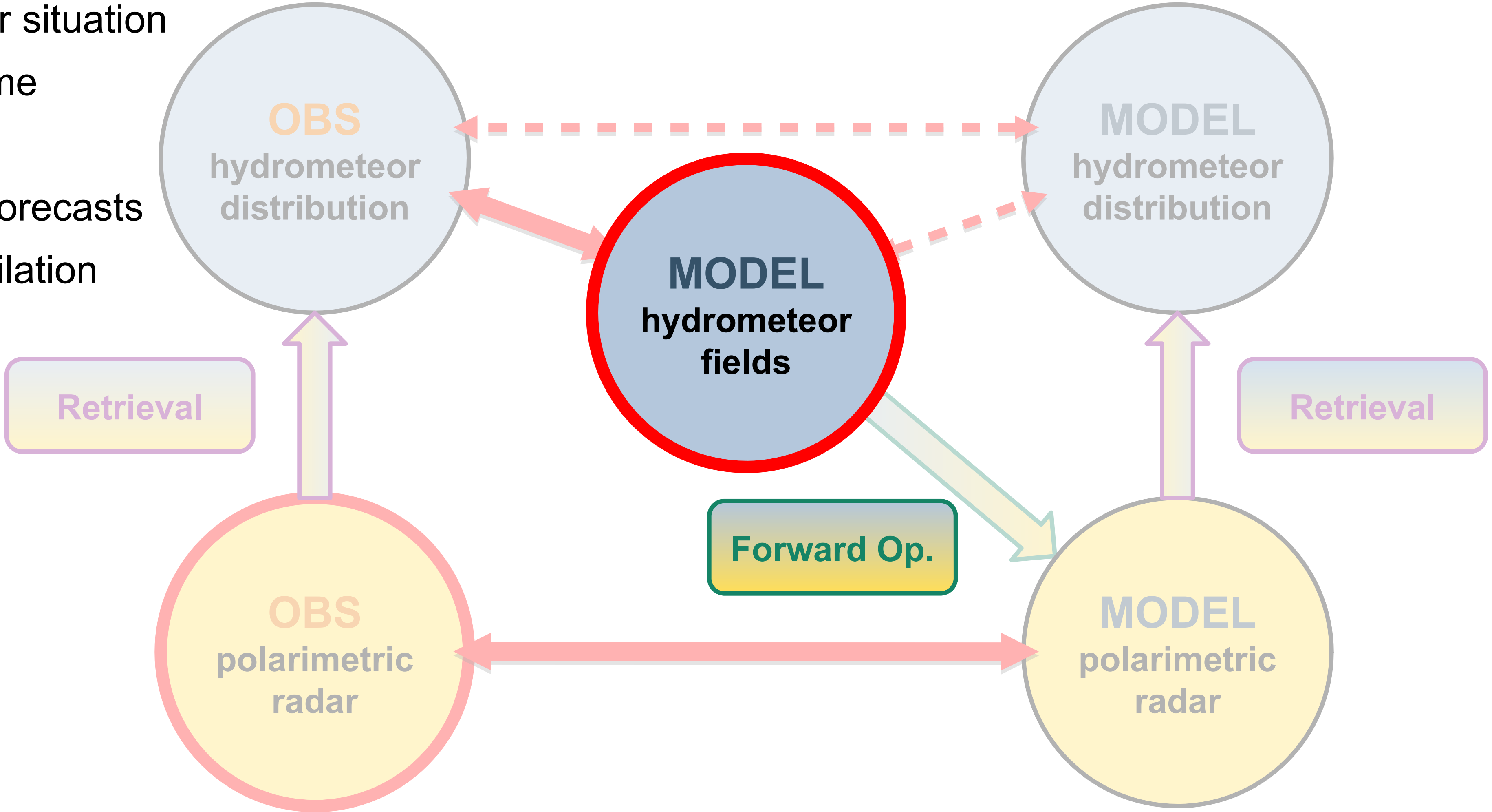
- hydrometeor distributions
- polarimetric moment distributions



Model evaluation: Method

➔ Model data best suitable for comparison/evaluation

- Represent the weather situation
  - match in space & time
- Options:
  - (long-running) free forecasts
  - frequent data assimilation

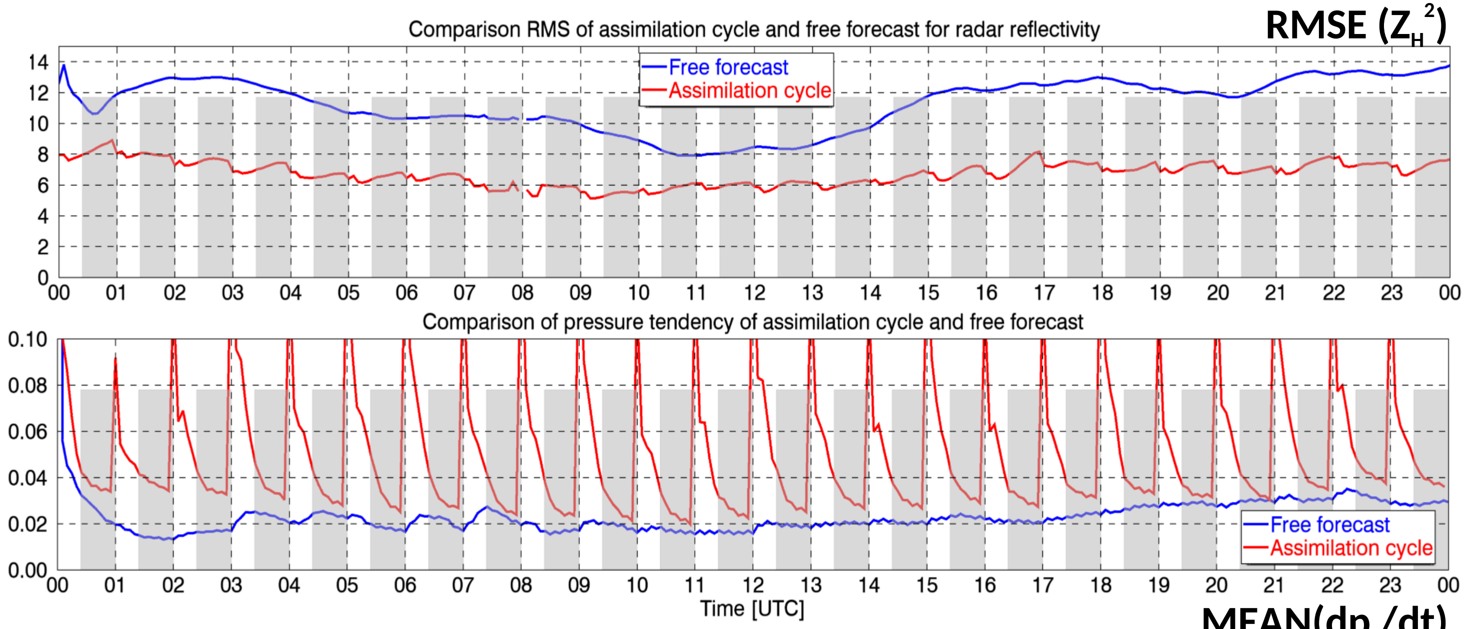


Model evaluation: Method

- ➔ Model data best suitable for comparison/evaluation
  - Represent the weather situation
    - match in space & time
  - Options:
    - (long-running) free forecasts
      + model characteristics
      - model-reality divergence
    - frequent data assimilation
      + better model-reality agreement
      - model-inconsistent DA states

= measure of model-reality match

RMSE (Z_H^2)



MEAN(dp_s/dt)

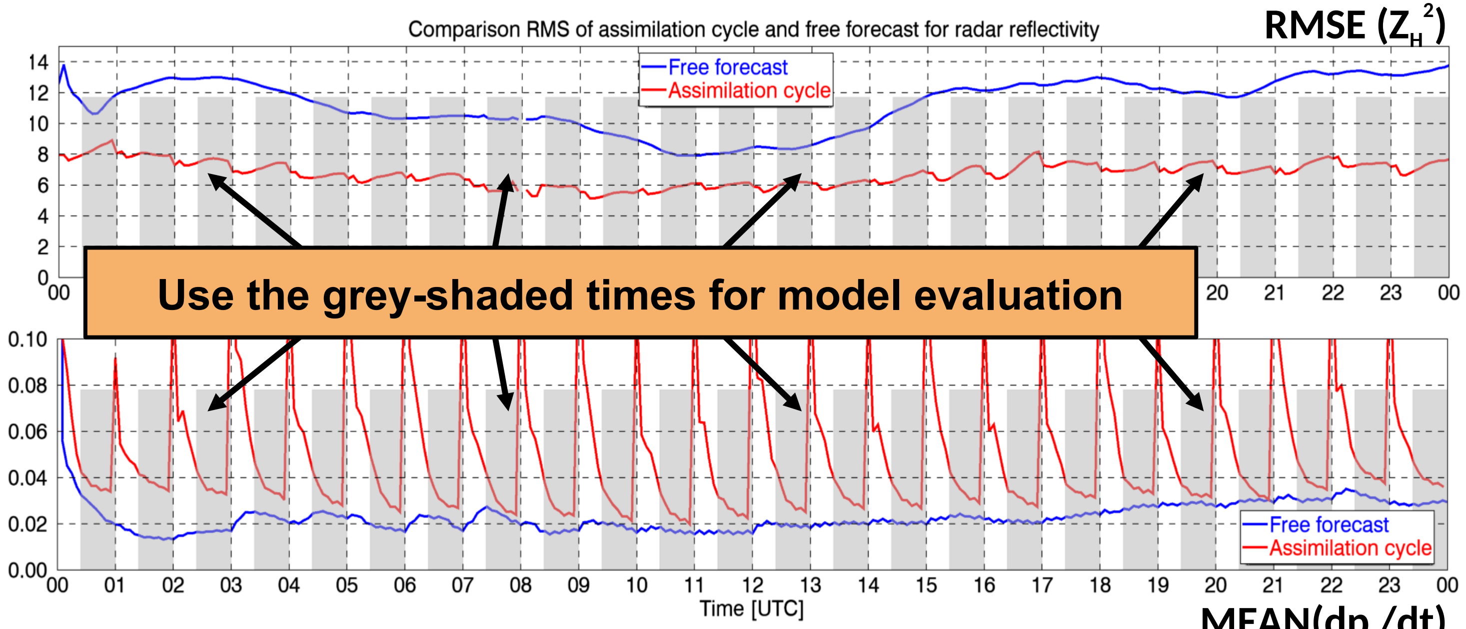
= measure of model „imbalance“

Model evaluation: Method

- Model data best suitable for comparison/evaluation
  - Represent the weather situation
    - match in space & time
  - Options:
    - (long-running) free forecasts
      + model characteristics
      - model-reality divergence
    - frequent data assimilation
      + better model-reality agreement
      - model-inconsistent DA states
- (our) Solution:
    - frequent DA (1h), but avoid spin-up time range (~20min)
      - data gaps :-/

= measure of model-reality match

RMSE (Z_H^2)



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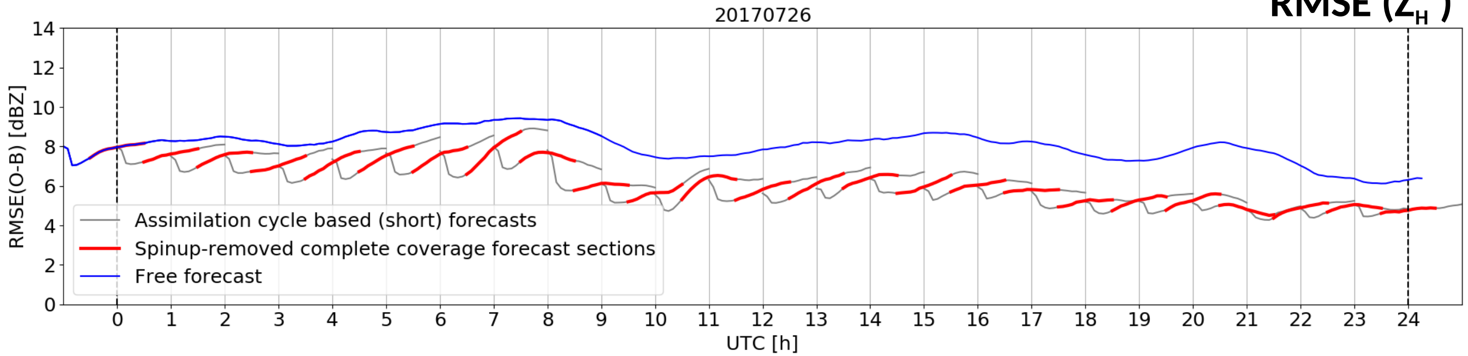
  - frequent data assimilation
    + better model-reality agreement
    - model-inconsistent DA states

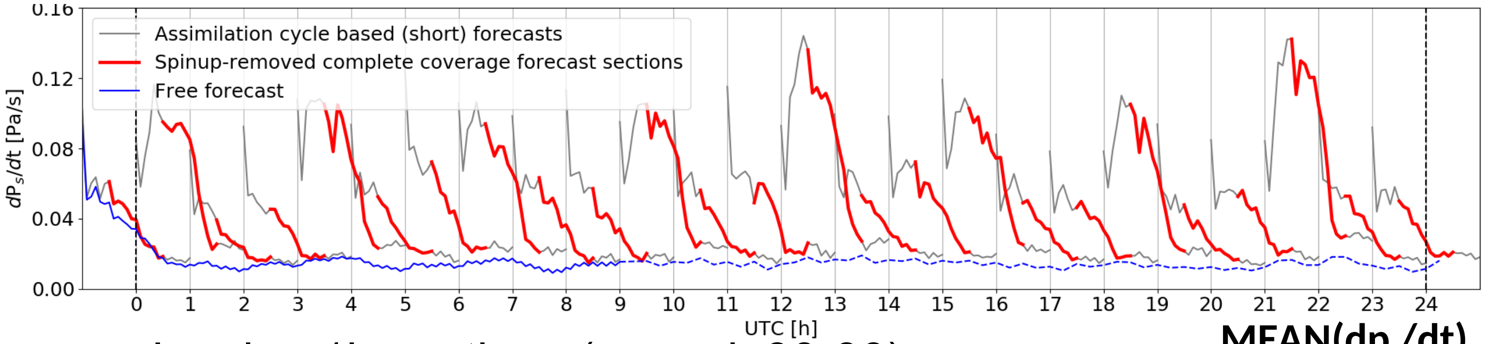
➔ (our final) Solution:

- hybrid: 1h-DA + 2h forecasts & use non-overlapping 1h-sections (e.g. min30-90)
  + model-consistent
  + gap-free
  - discontinuous

= measure of model-reality match

RMSE (Z_H^2)





MEAN(dp_s/dt)

= measure of model „imbalance“

Example: 17/07/26, stratiform

Model evaluation: Method

➔ Model data best suitable for comparison/evaluation

- Represent the weather situation
  - match in space & time
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  - (long-running) free forecasts
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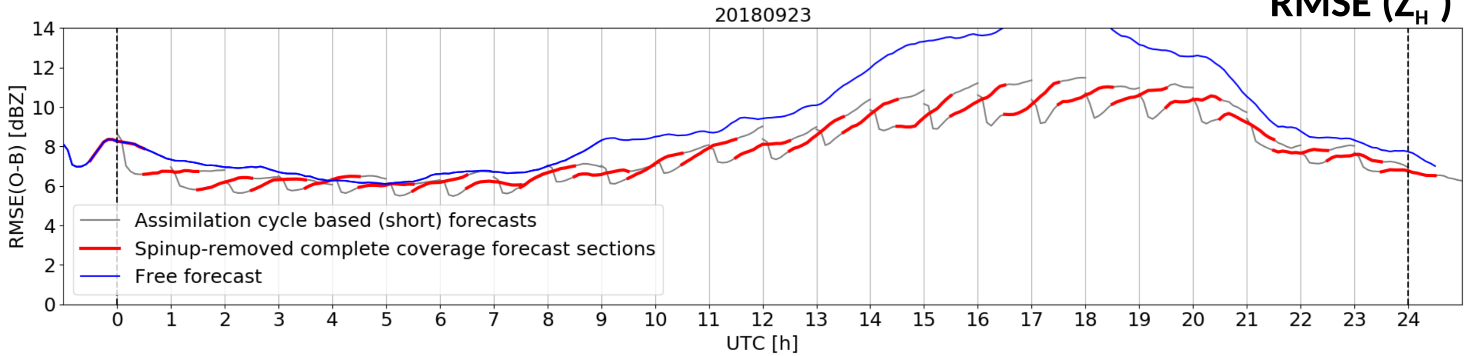
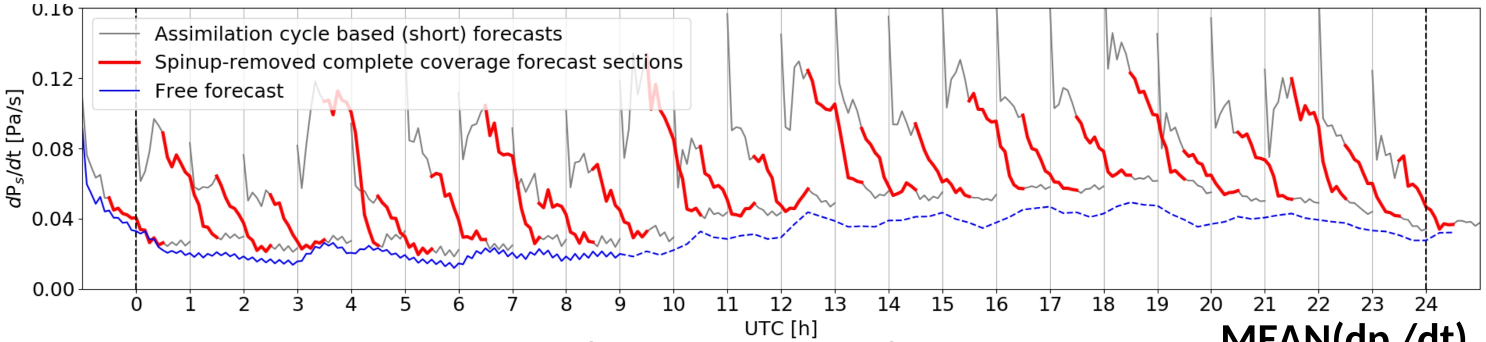
= measure of model-reality match

RMSE (Z_H^2)





MEAN(dp_s/dt)

= measure of model „imbalance“

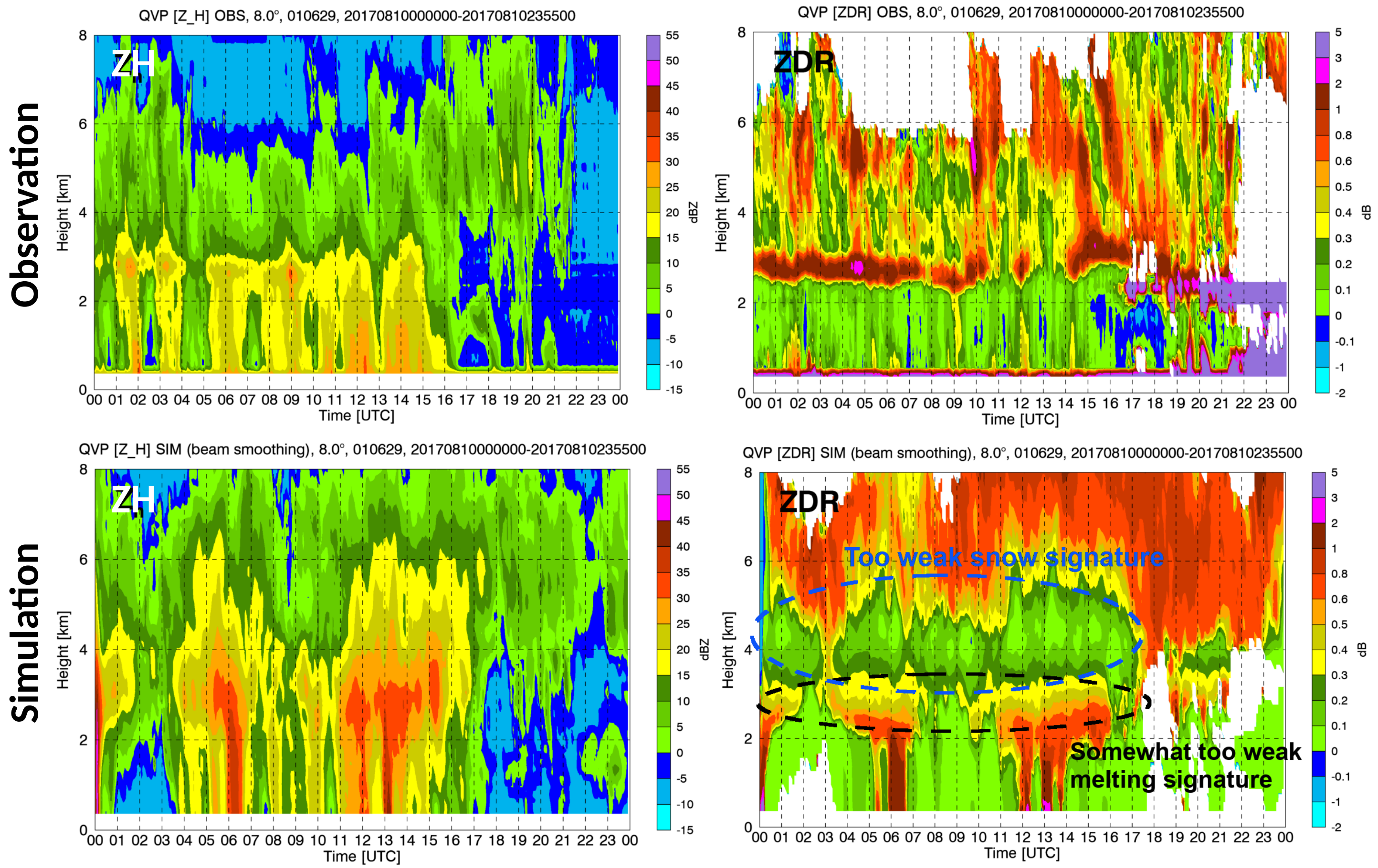
Example: 18/09/23, mixed

➔ (our final) Solution:

- hybrid: 1h-DA + 2h forecasts & use non-overlapping 1h-sections (e.g. min30-90)
  + model-consistent
  + gap-free
  - discontinuous
- all together 10 case days (5conv + 4strat + 1mixed)
  - precip & volume scans of DWD‘s 17-station C-band radar network

Model evaluation: Analysis – QVPs (per station & sel. elev.)

- Example from continuous 1h-DA (spinup time ranges included)
  - 17/08/10
  - stratiform
  - elev=8°



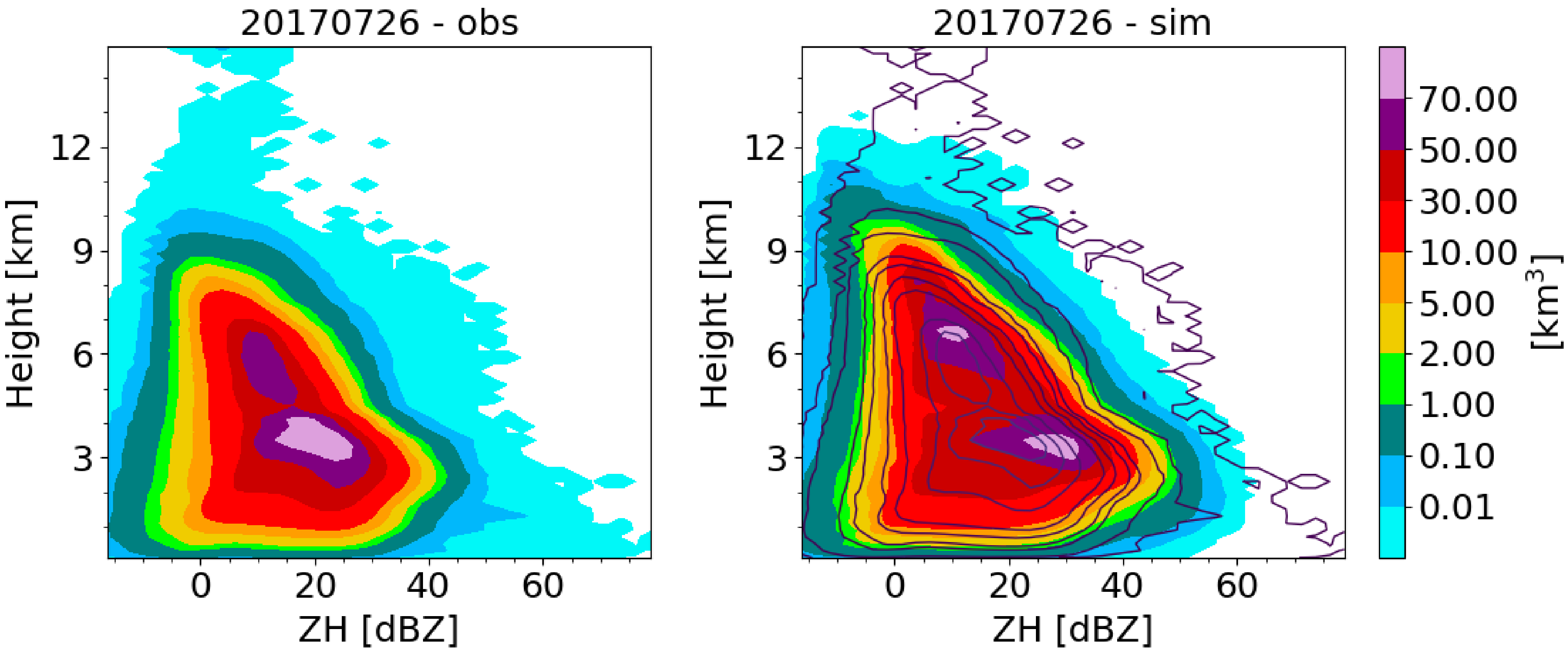
- Persistent issue: **lack of polarimetric signatures** in dendritic growth/ aggregation layers

  (not unique to EMVORADO or ICON)

Model evaluation: Analysis – CFADs (all stations & elevs)

➔ Reflectivity (Z_H)

- 17/07/26, stratiform
- hybrid 1h-DA/2h-forecast (incl. overlap)



Model evaluation: Analysis – CFADs (all stations & elevs)

➔ Differential reflectivity (Z_{DR})

- 17/07/26, stratiform
- hybrid 1h-DA/2h-forecast (incl. overlap)

TBD

Model evaluation: Analysis – CFADs (all stations & elevs)

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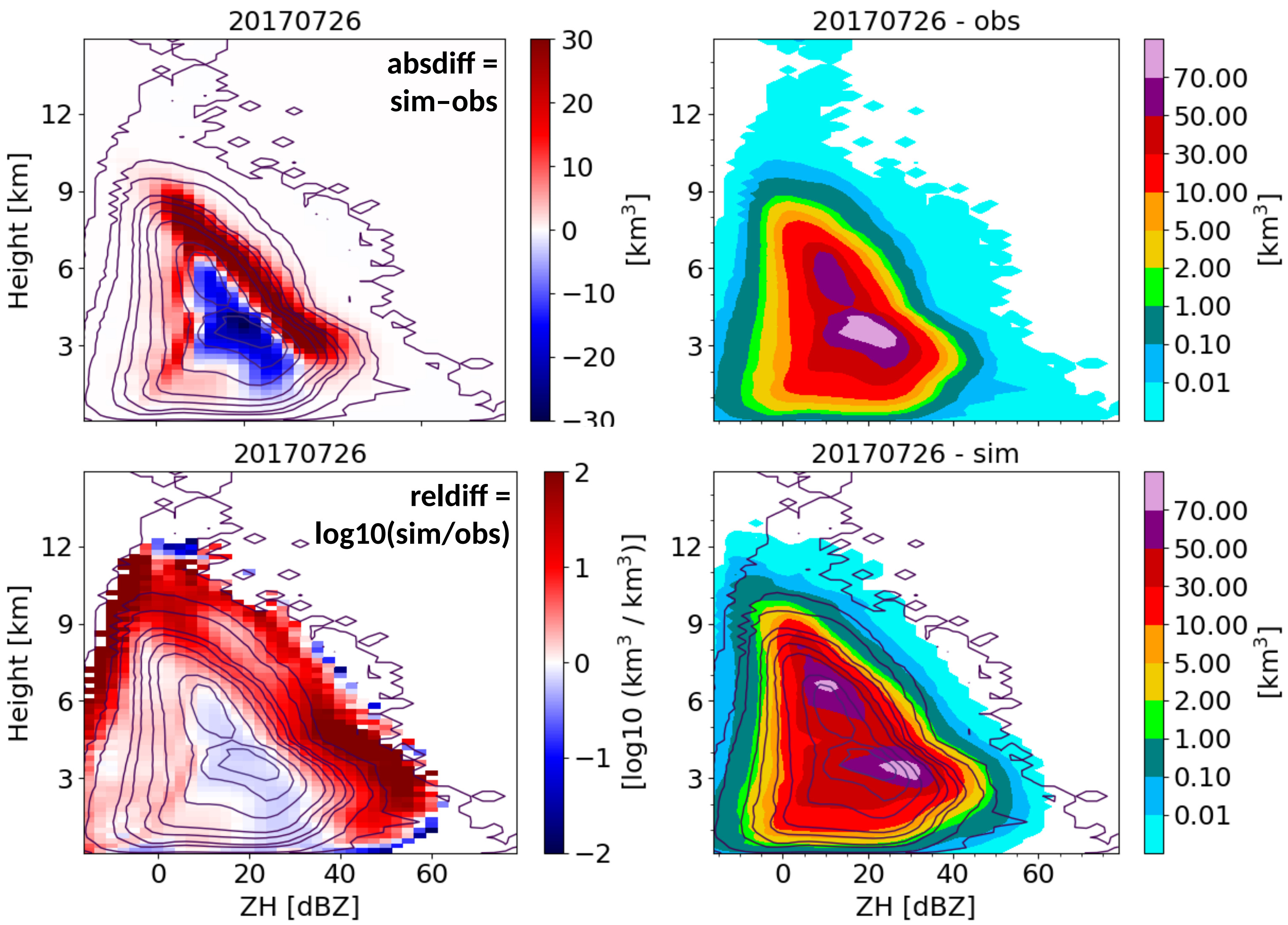
➔ Reflectivity (Z_H)

- 17/07/26, stratiform
- hybrid 1h-DA/2h-forecast (incl. overlap)



Model evaluation: Analysis – CFADs (all stations & elevs)

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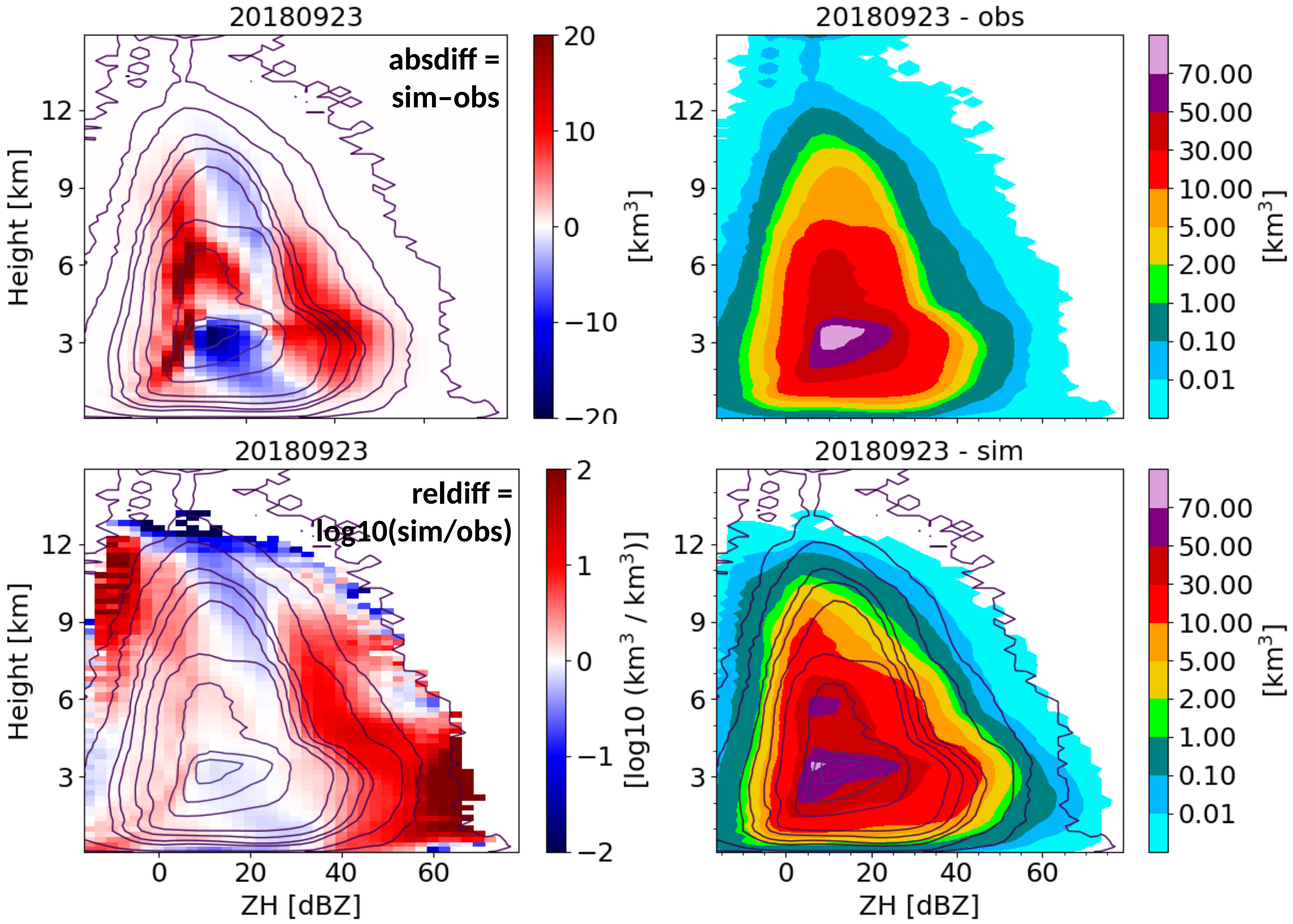
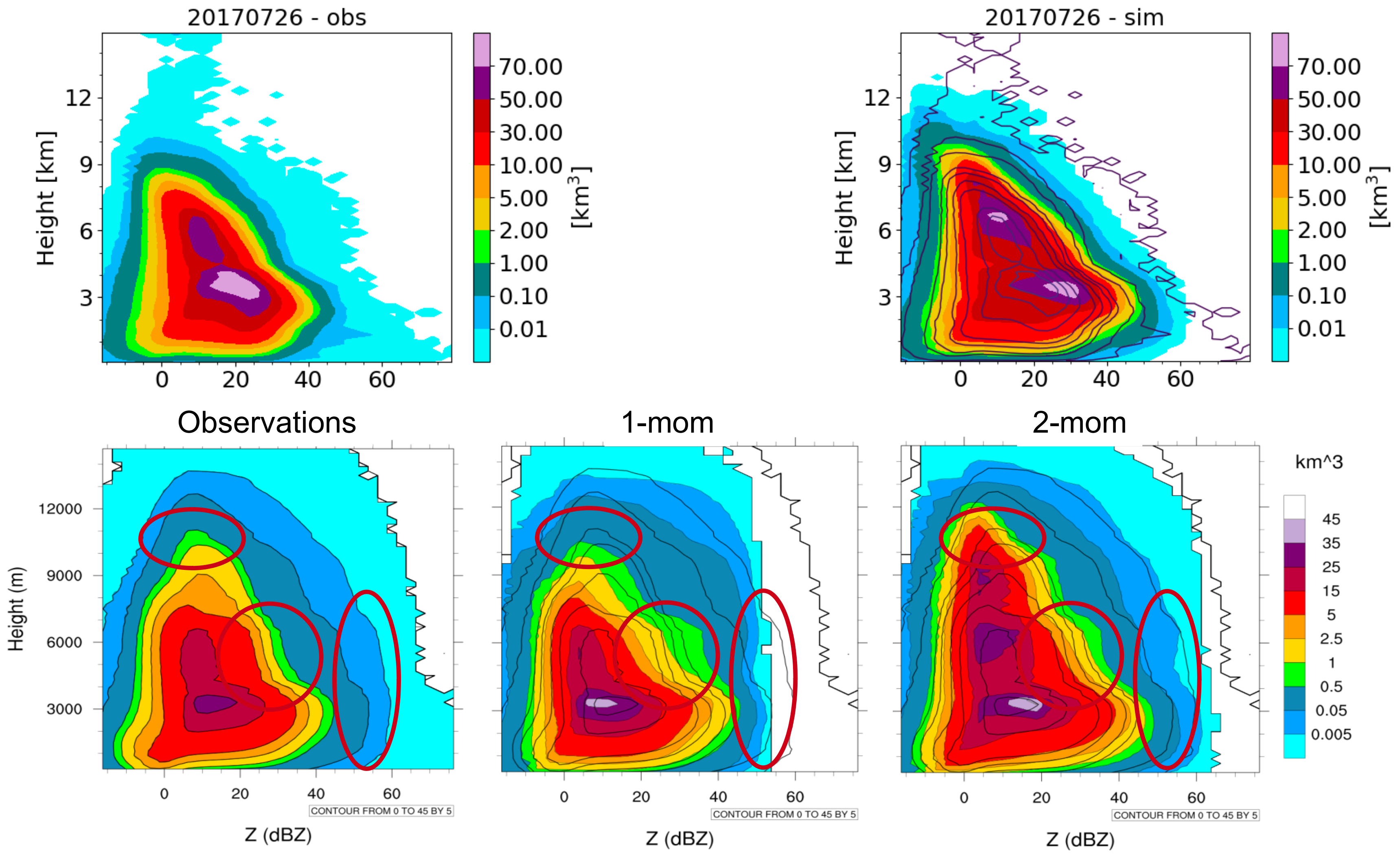
- ➔ Reflectivity (Z_H)
  - 18/09/23, mixed
  - hybrid 1h-DA/2h-forecast (incl. overlap)



Model evaluation: Analysis – CFADs (all stations & elevs)

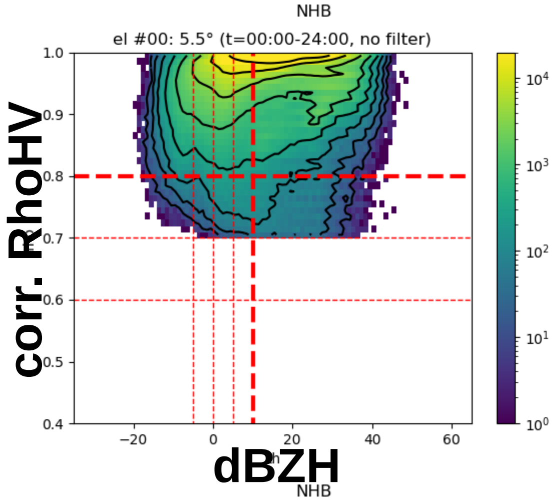
- ➔ Comparison to ICON(?)-D2 case study by A. de Lozar (date & situation unknown)



Model evaluation: Obs data quality

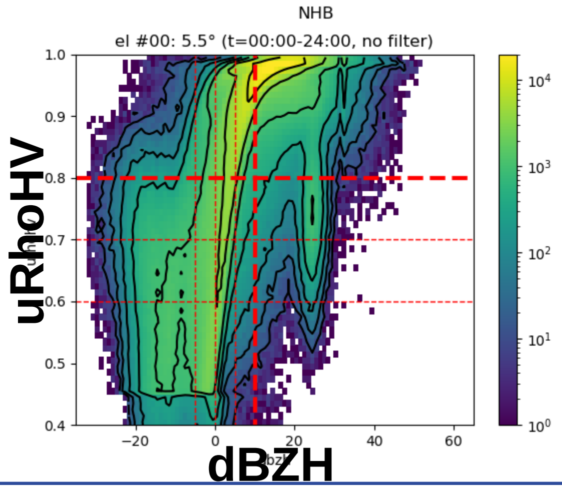
- ➔ Wealth of data from DWD‘s operational radar network (5min x 17stations x 10+1elevs over years)
- ➔ But, **polarimetric data processing / quality assurance not (yet) as mature**
  - DWD‘s focus is on **nowcasting** & forecasting
    - radar processing not (always) backward compatible
    - „suggested“ usage (e.g. Z>10dB) removes plenty of model-eval interesting data
  - there‘s things happening, though...
    - QA-ZDR in DB since Sept‘21
    - KDP-QA under development
    - RhoHV corr. implemented

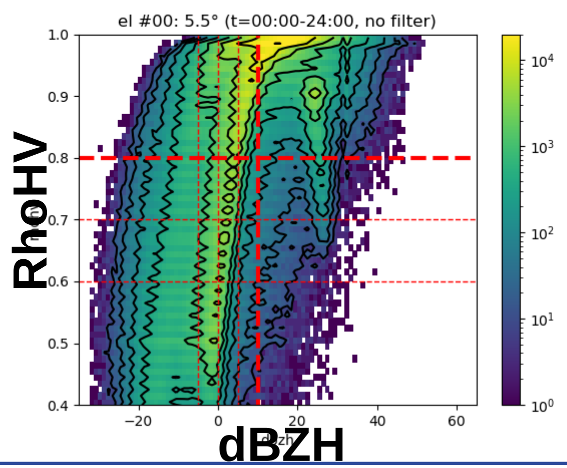
RhoHV



UBonn (post-)processed

17-07-25





QA-processed (POLARA): RhoHV not QA‘ed

Station-processed

Outlook

- Upcoming events:
  - PROM short course at ERAD (22/08/28)
  - Pol-EMVORADO workshop within PROM (tbd – 22/10/xx?)

- EMVORADO development (incl. PRISTINE)
  - make more flexible & easier to use: user controlable (target: for ERAD-SC / PROM-PFO-WS)
    - shape & orientation parametrizations; hydrometeor morphology; ...
  - explicit orientation integration; allow non-oblate shaped hydrometeors
  - digest external scattering data (e.g. DDA for/from PRISTINE)
  - melting scheme revision, ...
- DA refinements
  - Latent heat nudging, …
- Processing & analysis tool extention/adaption to polarimetric data
  - BACY, CFADs, ...

The end

(More) Questions?

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Extra slides

Licensing

- EMVORADO is considered a part of DACE, which is official „COSMO-software“, similar to COSMO-model, fieldextra, etc. (Annex A of COSMO treaty)
- EMVORADO is also implemented in ICON, in which case it is considered „ICON-software“ and part of the ICON license.

4 Cases:

- Usage of EMVORADO in ICON: you need an ICON license
- Usage of EMVORADO in COSMO: you need a COSMO license
- Usage of Stand-alone version of EMVORADO: You need a COSMO license
- In case of common research projects to further develop EMVORADO, there needs to be a mutual cooperation agreement. We are currently working out the blueprint of such an agreement with our legal department. It is required, because
  - we want to make sure that results/improvements achieved by the project may be used by each partner afterwards
  - software developments may be freely distributed to others by each of the partners afterwards

Implementations

- Standalone version (protected, need COSMO license):
  - git@gitlab.dkrz.de:dace_projects/emvorado-offline.git

- ICON-NWP branch *icon-nwp/icon-nwp-dev* (every ICON user can use, need ICON license)

  $> git clone git@gitlab.dkrz.de:icon/icon-nwp.git

  $> git submodule update --init --recursive

  $> ./config/dwd/<your-config-wrapper> --enable-emvorado

- COSMO branch *ublahak-emvorado-updates_202012* (every COSMO user can use, need COSMO license)

Polarimetric forward operator: Status summary

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→ Computational speed: **parallelization + bulk scattering lookup tables**

- tabulation of additive components per hydrometeor class
- over total (1mom) or mean (2mom) bulk mass q_x + ambient temperature T + max. melting temperature T_m

→ **Example: online in ICON-LAM** on DWD's NEX-SX Aurora HPC (128 vector processors)

- D2-domain, 2-mom microphysics, 6 hydromet. classes
- **24h** free **forecast** with **5' output** of **10-elev. volume scans** for **16** DWD C-band **radars (= 289 radar output times)**

Configuration	EMVORADO time [s] (incl. MPI comm.)	Total model time [s]	Increase [%]
CTRL (no EMVORADO)	-	680	-
E1: **Mie** (look-up), pencil beam, dBZ + v_r	15*	695	**2.2**
E2: T-matrix (look-up), pencil beam dBZ + all dualpol moments + v_r	**28***	**708**	**4.1**
E3: E2 + **vertical beam function smoothing** (5 auxiliary rays for quadrature)	51*	736	8.2

→ Computing time polarimetry (E2), one 5'-step, all 16 German C-band stations: 28 s / 289 = 0.1 s

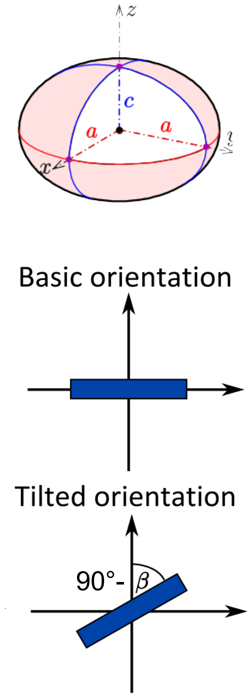
* if the look-up tables already exist; additional time to pre-compute look-up tables, depends on platform, may vary from few minutes to several days

Polarimetric forward operator: Status summary

- Approach: add polarimetry to EMVORADO, but **keep existing features & characteristics**
  - consistent model coupling, sensor (network) modelling
  - hydrometeor property assumptions
  - **speed**
- Added scattering model option: **T-Matrix** + angular moments
  - shape (AR), orientation (σ_β), melt fraction dependence from Ryzhkov et al. (2011)

*state-of-the-art, but **has** its **issues***

liquid	rain	ice	snow	graupel, hail	
Rayleigh	oblate spheroids	oblate spheroids	oblate spheroids	oblate spheroids	shape
-	Brandes (2002) f(deg4-in-D)	Matrosov (1996) thick plates aD^b	1.0-0.02*D 0.8 (D>10mm)	1.0-0.02*D 0.8 (D>10mm)	AR
-	10°	10°	40°	40°	σ_β
-	-	both: lin. in f_m to rain	both: lin in f_m to rain	AR: lin. in f_m between AR_{wet}=[AR_{dry},0.8,0.48,AR_{rain}] for f_m=[0,0.2,0.8,1] σ: lin. in f_m to rain	melting behaviour (f_m=mass melt fraction)



Application: Evaluate hydrometeor type representation

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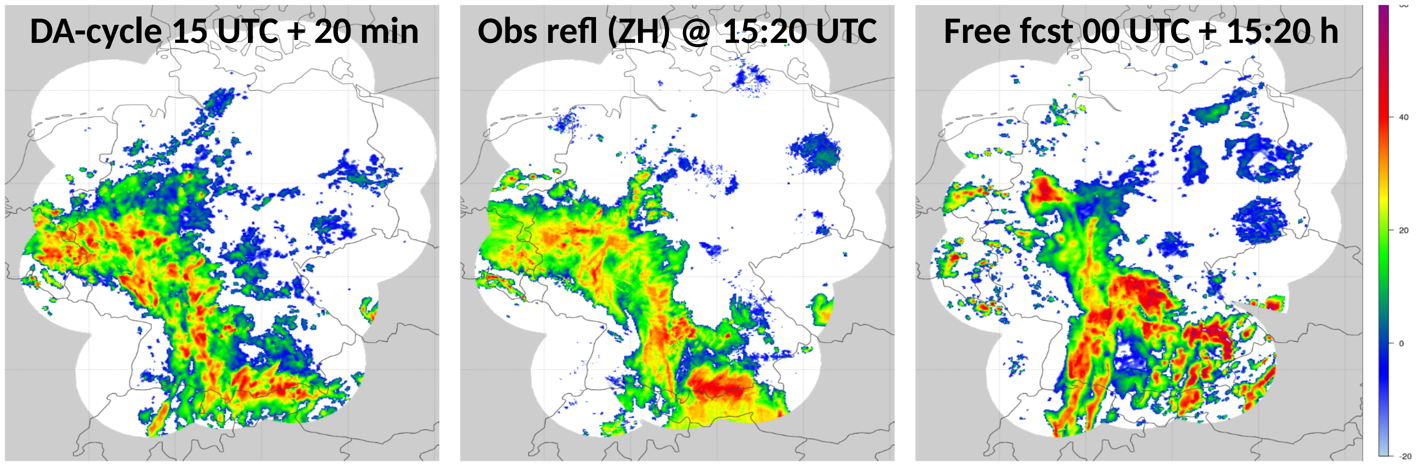
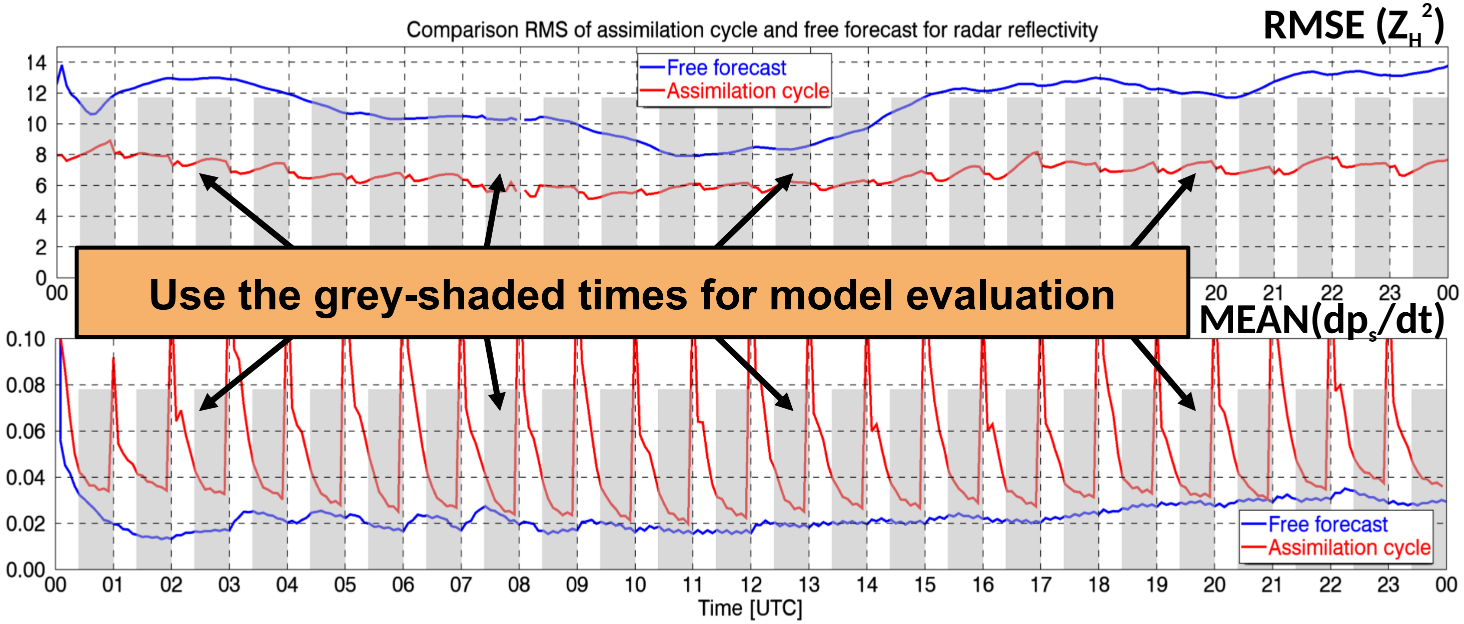
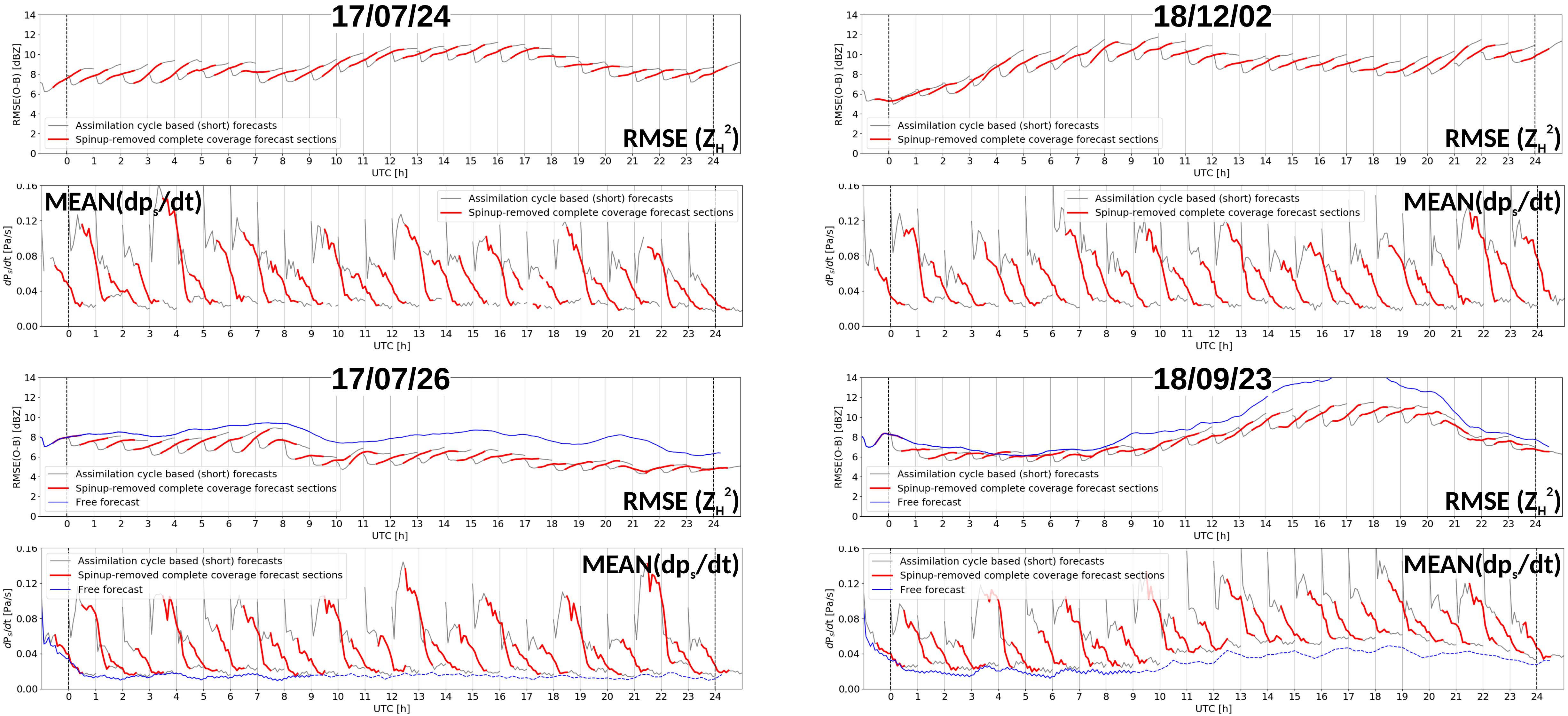
DWD

- ➔ Dual strategy (→ Pejcic): Comparisons of
  - **modelled** and retrieved **hydrometeor distributions** in space & time
  - **simulated** and observed distribution of **polarimetric moments**
- ➔ Atmospheric states from NWP modeling, here: ICON-LAM for selected case days
  - (a) 24h free forecast
  - (b) frequent data assimilation (BACY)
    - – shown: every 1h incl. CONV+ZH+Vr + 1h free forecast
    - – **now:** every 1h incl. CONV+ZH+Vr + 2h free **forecast (dual.pol)** for **gap-free time coverage**





Model evaluation: DA stats – stratiform & mixed cases



Model evaluation: DA stats – convective mixed cases

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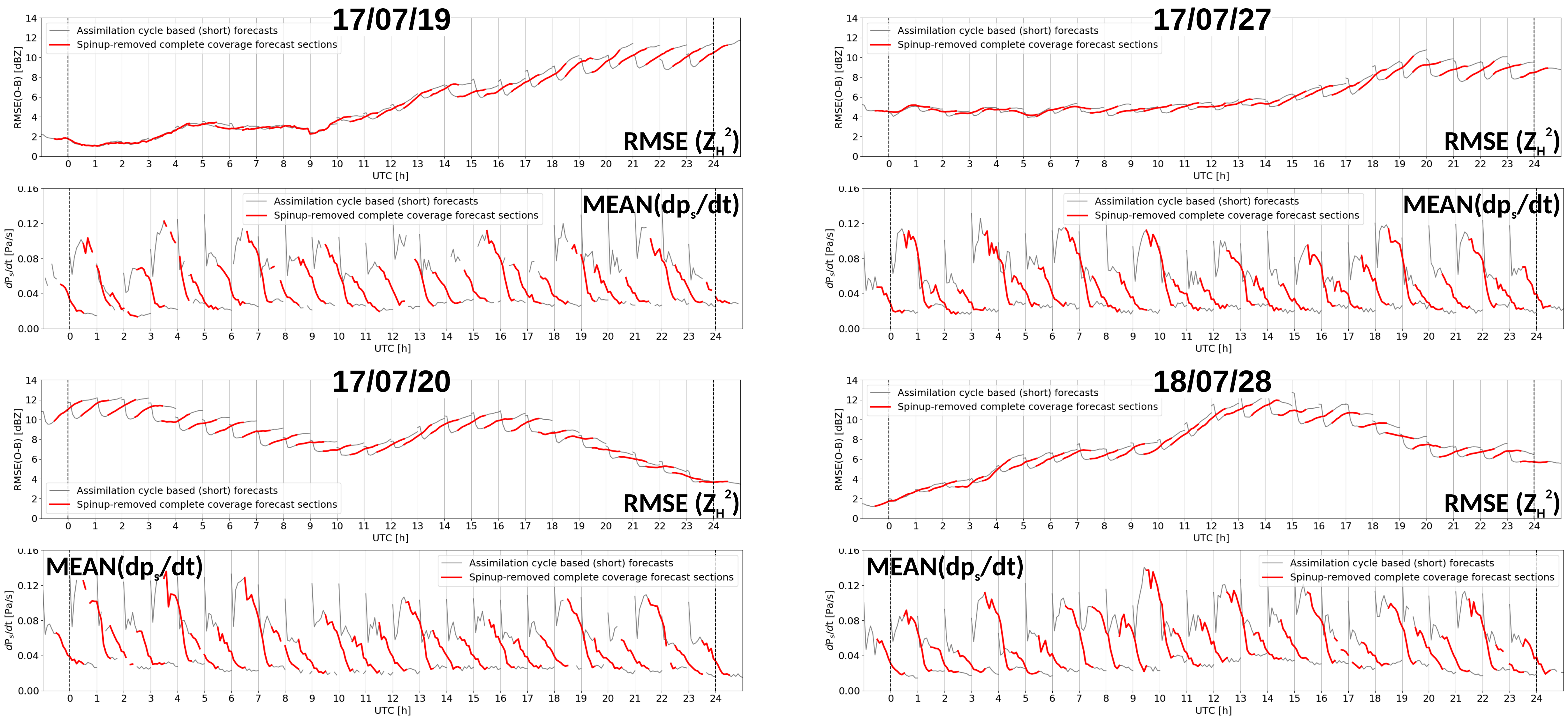

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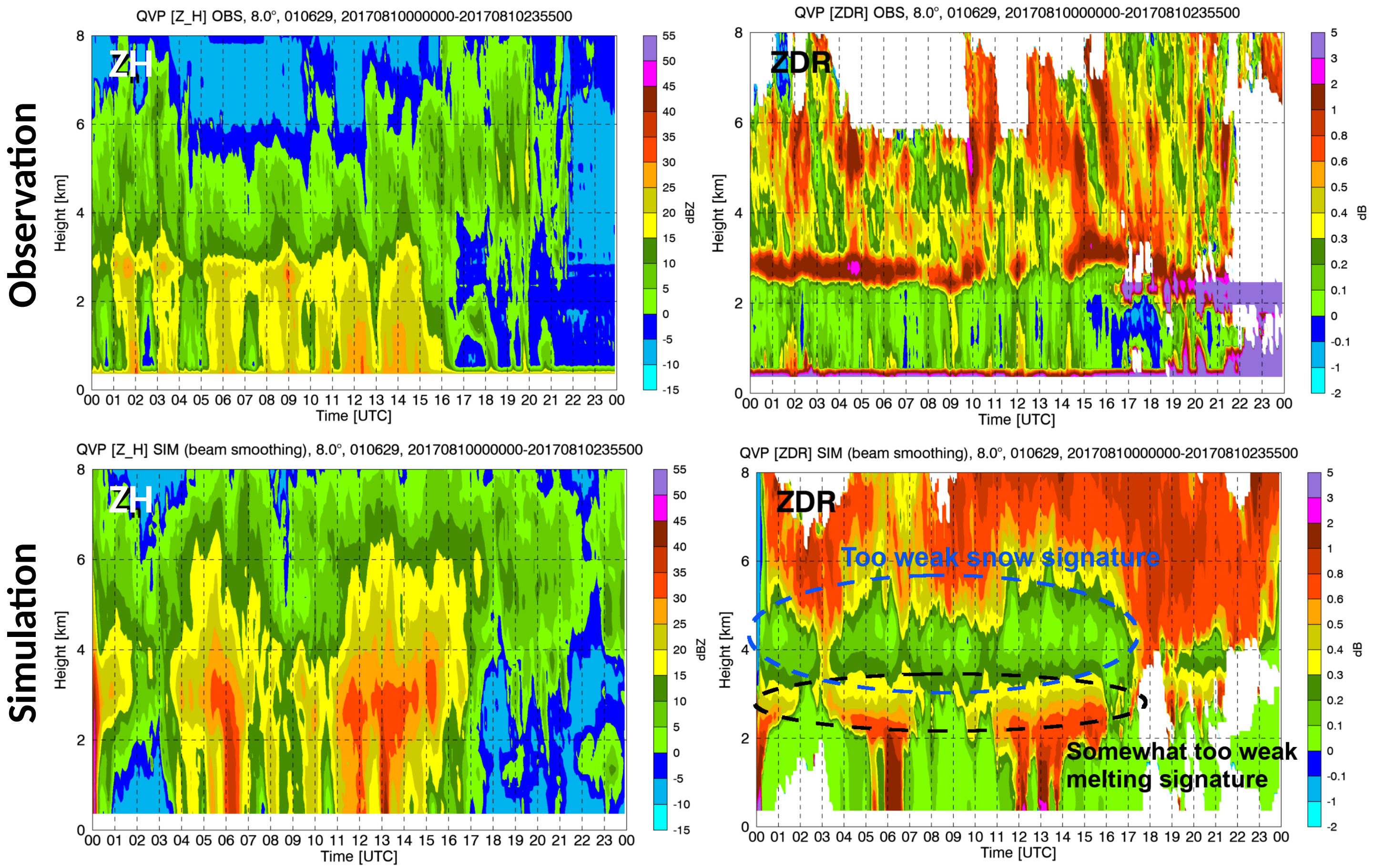
- Persistent issue: **lack of polarimetric signatures** in dendritic growth/aggregation layers **(not unique to EMVORADO or ICON)**

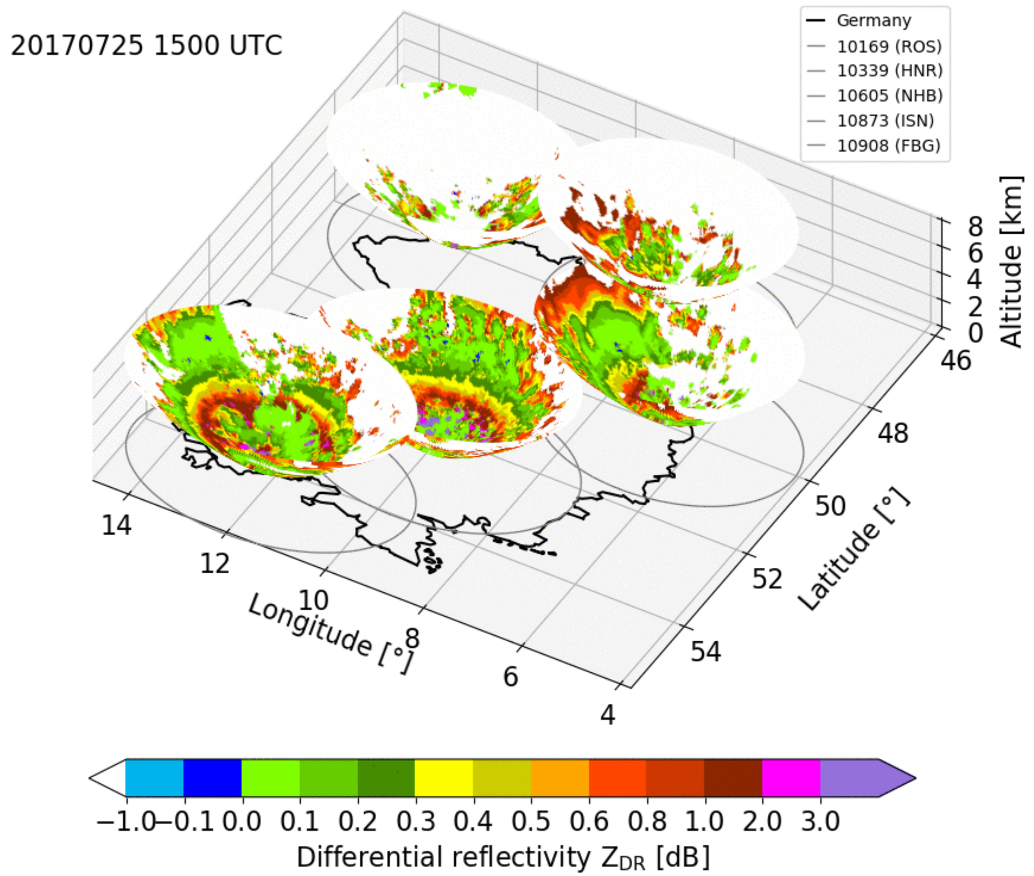


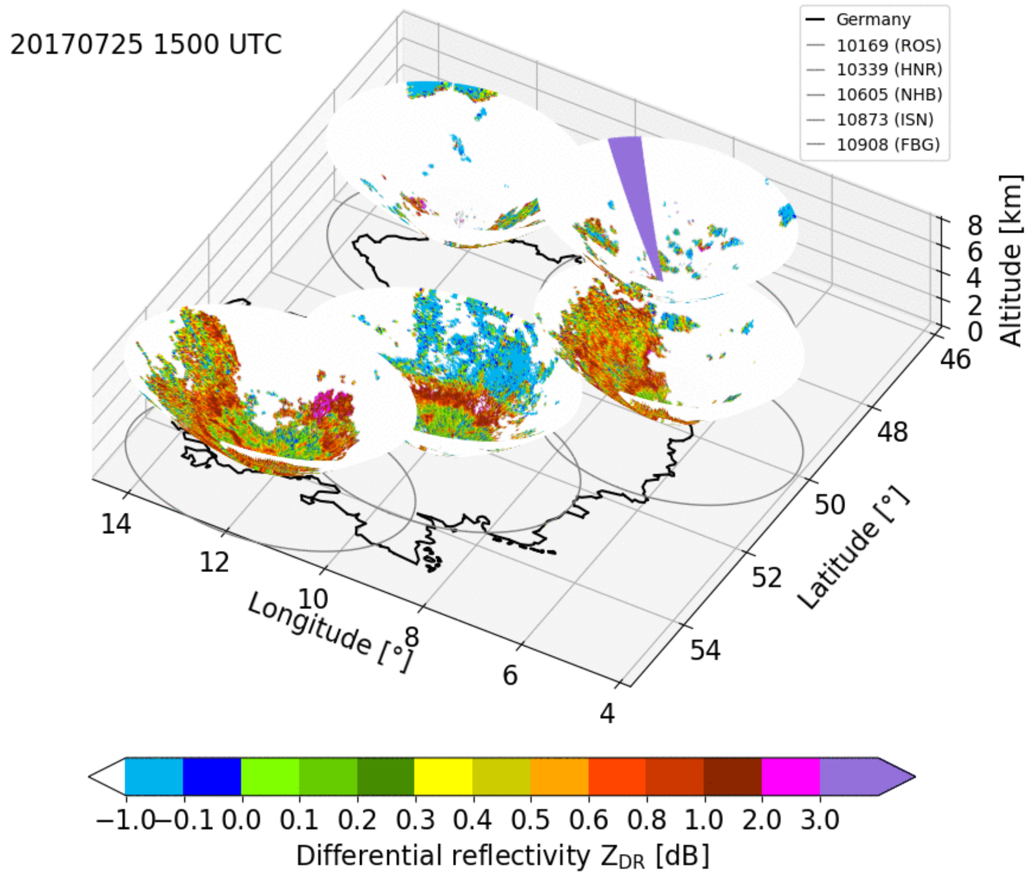
QVP time series of ZH (left) and ZDR (right) for a stratiform event on 10 August 2017, monitored by DWD‘s C-Band radar Offenthal at elevation angle 8°. Simulations (bottom) include vertical beam function averaging.

Application: Evaluate hydrometeor type representation

➔ Radar simulation output: Synthetic observations of polarimetric moments

- **equivalent to observations**: 10+1 elev. volume scans of 16 stations every 5‘ (**obs-governed, extendable**)
- shown: synthetic (left) vs. real (right) observations of ZDR (elev=1.5°) of a 2h forecast for 15UTC DA

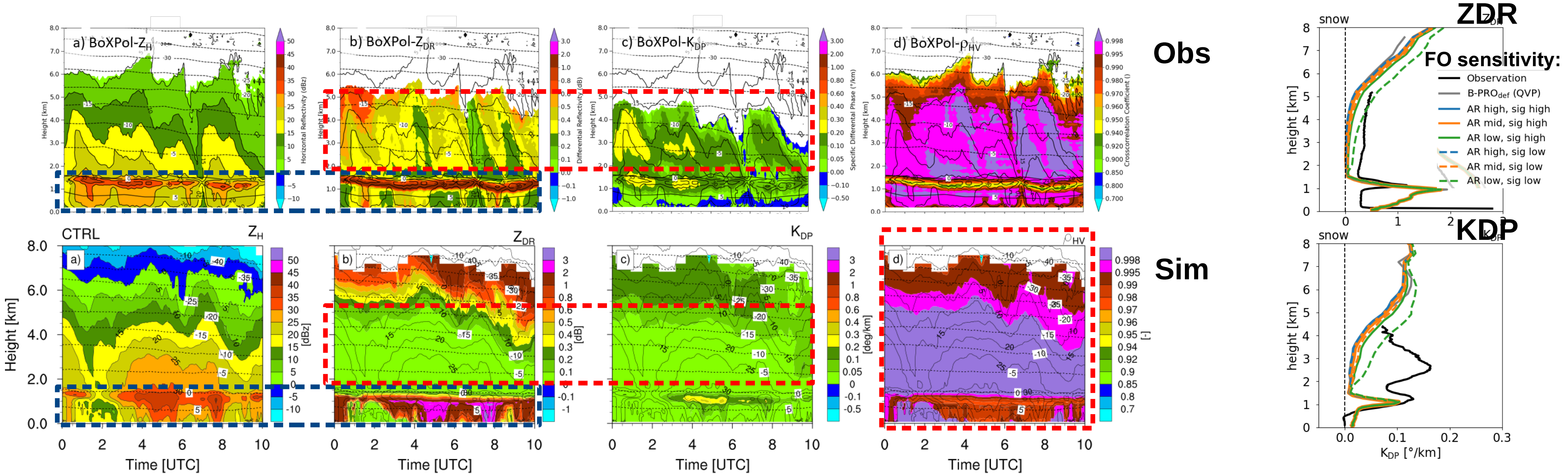




Polarimetric extention: Applications & Challenges

➔ Model evaluation (Shrestha et al., 2021):

- COSMO 2-mom of stratiform rain event, observed with X-band pol. radar at Bonn, Germany



➔ FO uncertainties & shortcomings:

- shape & orientation: choice of parametrizations, natural variability
- suitability of homogeneous models for fluffy, low effective density particles, eg snow aggregates

Polarimetric extention: (DA) Challenges

➔ FO uncertainties (non-**polarimetry** specific)

- **Particle model, shape & orientation**
- Effective medium approximation of refractive index
- Melting scheme
- Understanding of the measurement process:
  beam smoothing of pol. parameters (Z-weighted?)

➔ Technical

- LUT calc time consuming
  (but: calculated once & re-used; then as fast as Mie/Rayleigh!)
- Memory requirements (5-10 times Mie)
- Lacking implementation of superobbing & feedback files

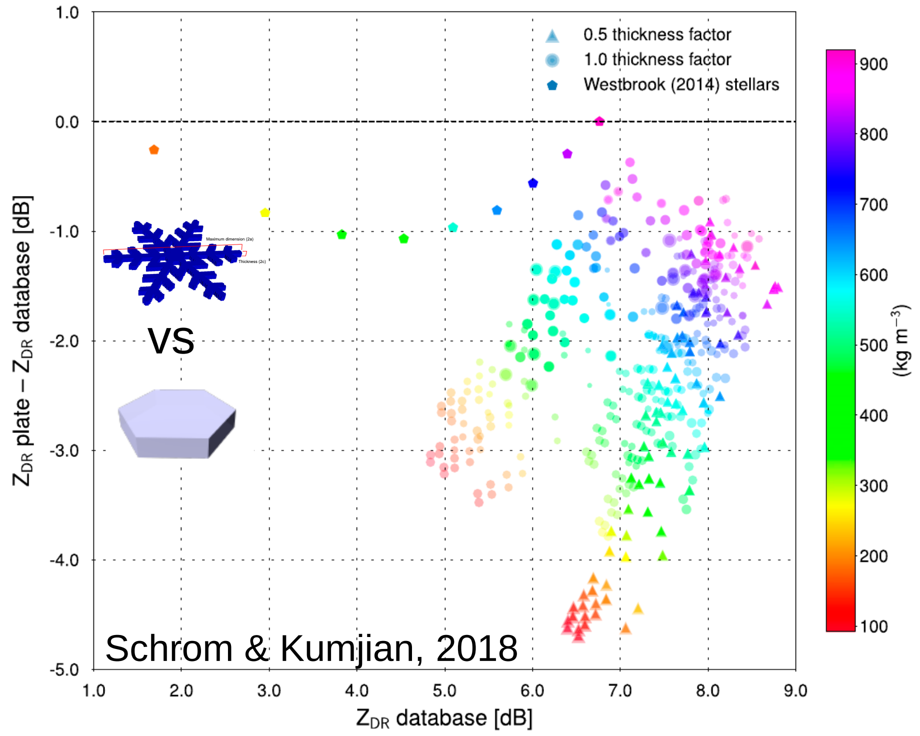
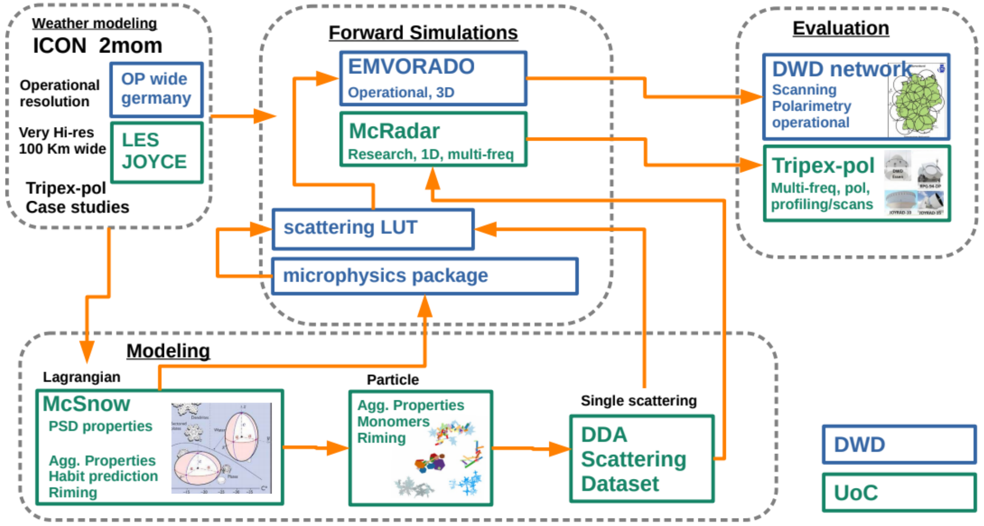


FIG. 3. As in Fig. 1, but for Z_{DR}. The size of the markers indicating the Westbrook (2014) particles are enlarged for the purposes of interpretation and therefore do not correspond in scale to the size of the markers depicting the Lu et al. (2016) branched planar crystals.

Polarimetric extention: Outlook – PROM-2 PRISTINE



- ➔ FO uncertainties: **Particle model, shape & orientation**

- ➔ Issues:
  - none-TMat approaches are costly
  - scattering data with polarimetry & orientation is sparse
  - availability of model-consistent habit & habit selection

- ➔ Solution approach: a model-guided database
  - model shape & occurence of hydrometeors (snow primarily), derive scatt. props from DDA
    - Lagragian particle model + aggregation/riming model
    - starting from ICON model state
  - DDA-based bulk scatt LUTs for EMVORADO
    - selection from scatt. DB in dependence of model state („habit prediction“)
    - consistent with model

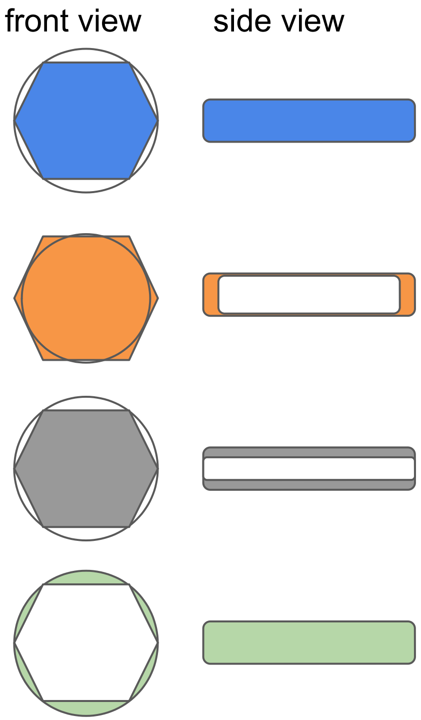
Tmatrix accuracy various approaches

SPP 2115

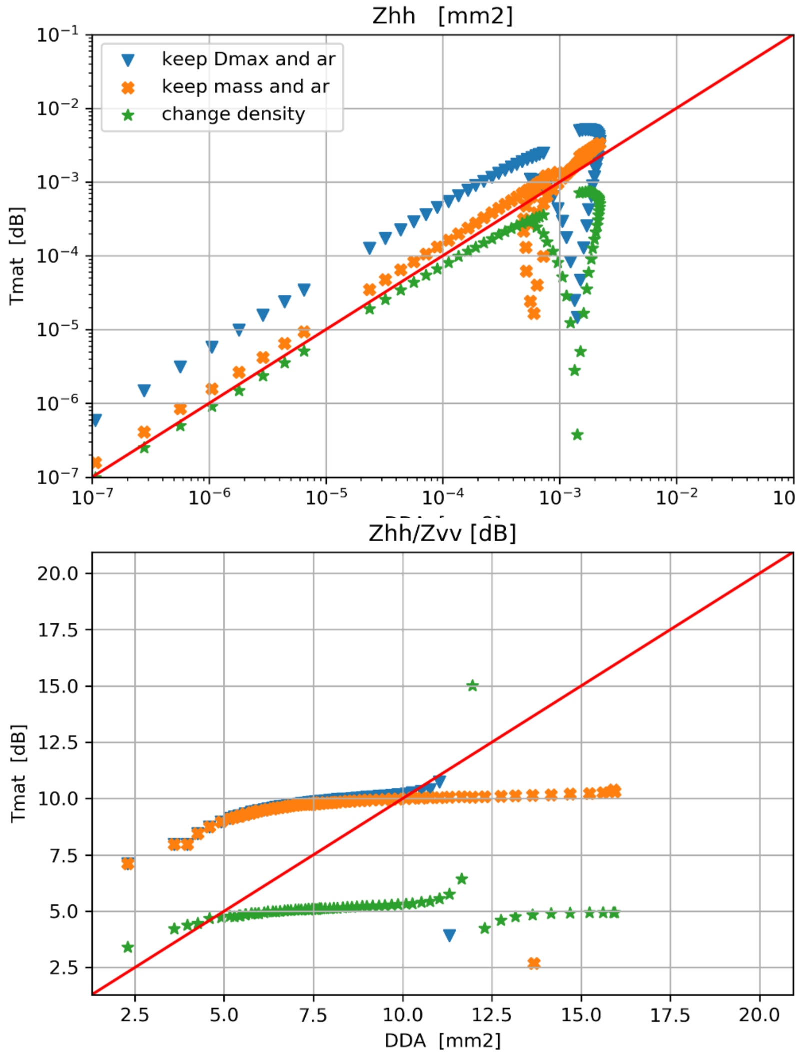
spheroidal or cylindric approximation of shape

4 extreme approaches
(D, m, ar, density):

1) increase mass
2) reduce max dimension
3) **change aspect** (make it thinner)
4) **reduce density**



Example with dendrites



There is no unique method.
It is possible to “tune” individual spheroids to match (some) scattering properties of complex shaped particles, but not consistently over size and wavelength ranges.

Reduced density approach

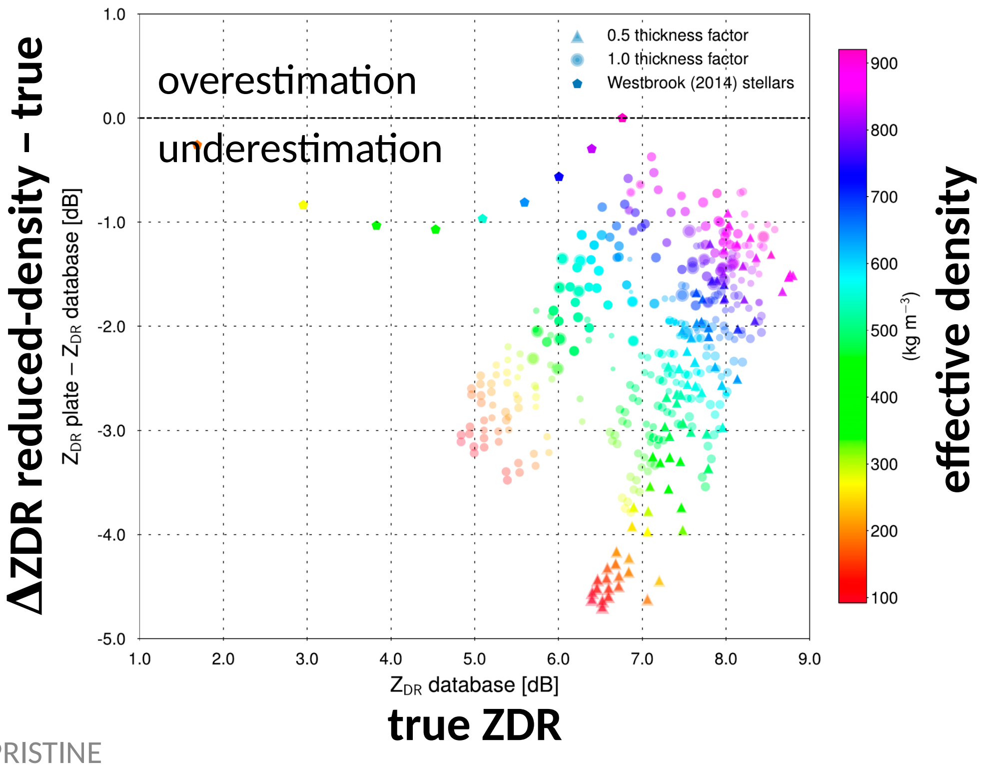
SPP 2115

Probably the most popular approach to setup particles consistent to model constraints (keeping m, D, and aspect ratio unchanged) with T-Matrix suitable shapes.

T-Matrix based simulations show a **consistent deficit** in terms of **polarimetric response** in the dendritic growth layer where large, “fluffy” particles prevail.

Schrom & Kumjian (2018)

- assessed errors in polarimetric scattering properties of homogeneous reduced-density particles as proxies of branched planar crystals (both from DDA)
- found persistent underestimation of ZDR, the worse the less dense
- provided detailed explanation for the **role of internal structure** from dipole interactions

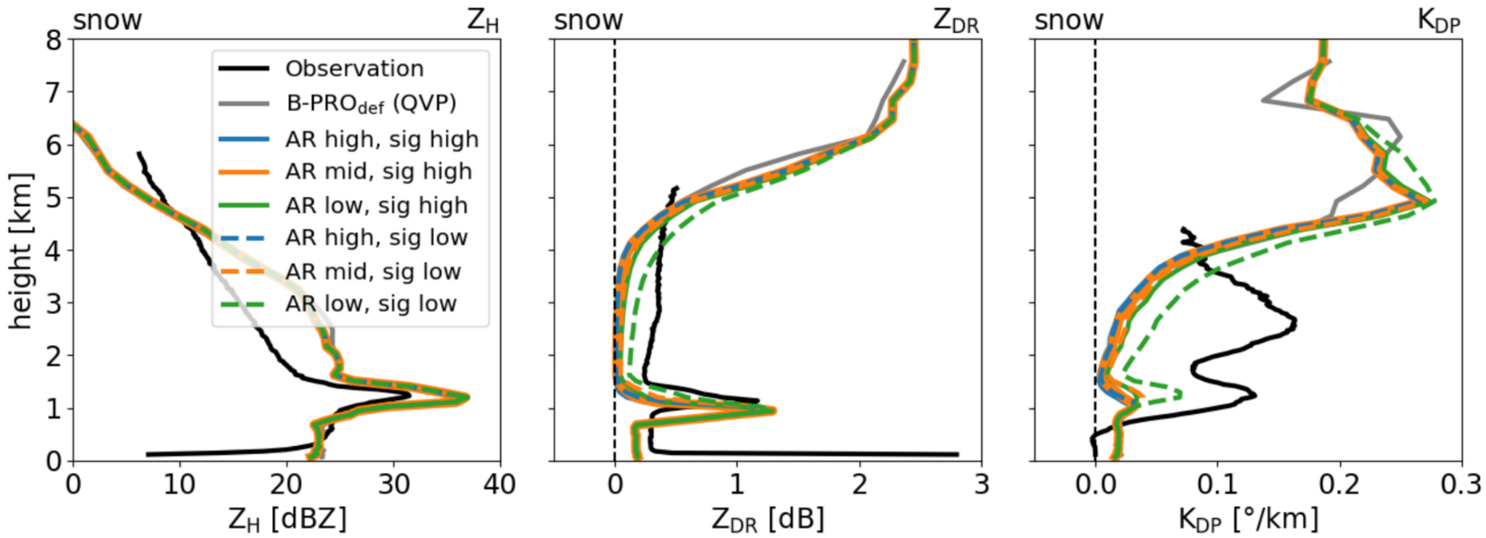


… consistent deficit in terms of polarimetric response …

There are further explanations for lack of polarimetric signals!

FO uncertainties that can contribute include, e.g.,

- melting models
- dielectric properties (primarily of air-ice(-water) mixtures)
- *shape and orientation assumptions*



	snow
AR_{high}	Ryzhkov et al. (2011) $max(1.0 - 20D, 0.8)$
AR_{mid}	**Xie et al. (2016)** $\boldsymbol{max(0.7 - 10D, 0.5)}$
AR_{low}	Dunnavan et al. (2019) 0.4
σ_{high}	**Ryzhkov et al. (2011)** **40°**
σ_{low}	Matsui et al. (2019) 20°

Shrestha et al. (2021), GMDD

DGL signatures in other PFOs

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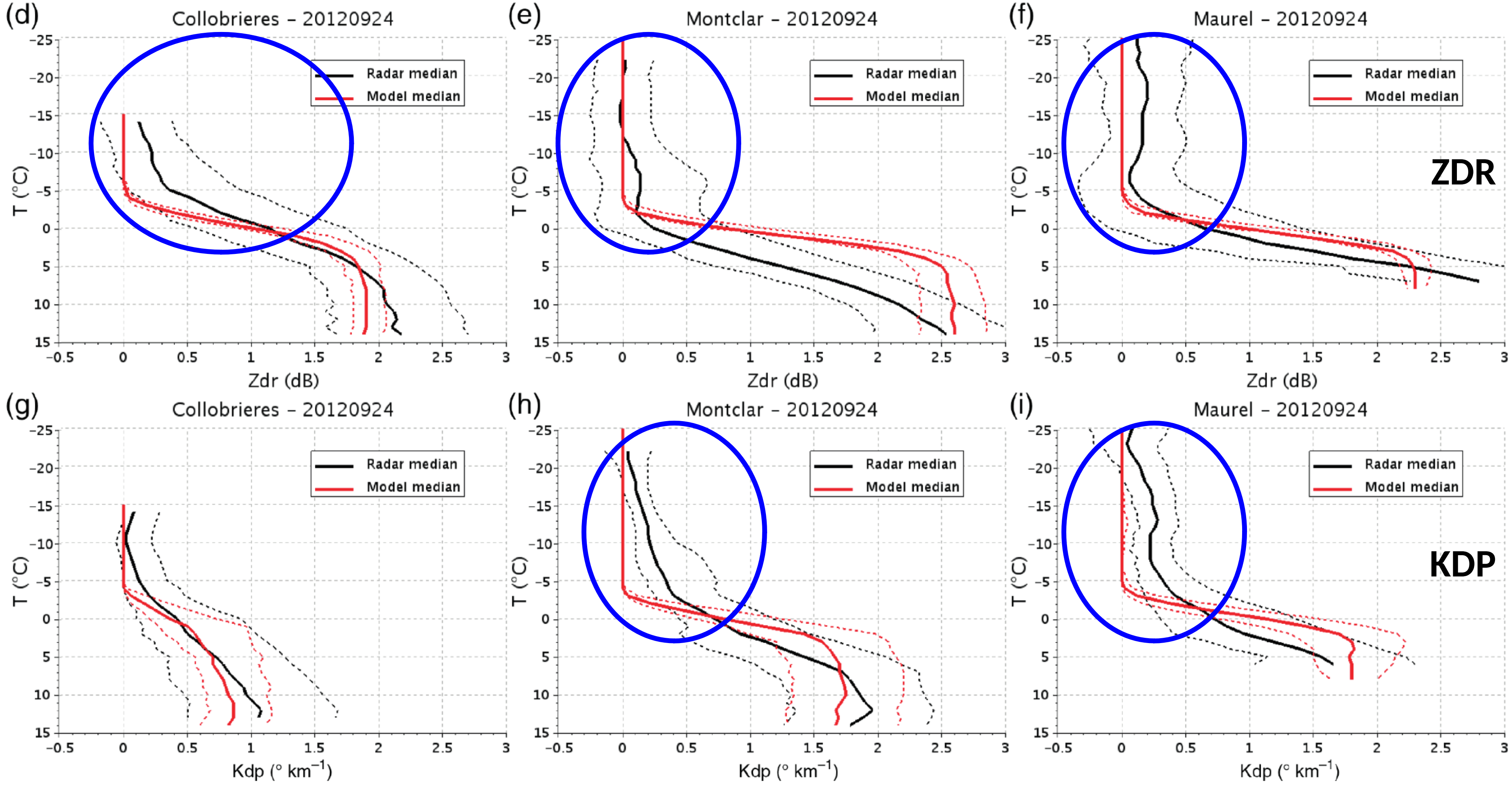
… **consistent deficit** in terms of **polarimetric response** …

S-band C-band X-band



FO: own unnamed, Caumont06-based
Model: Meso-NH

PRISTINE

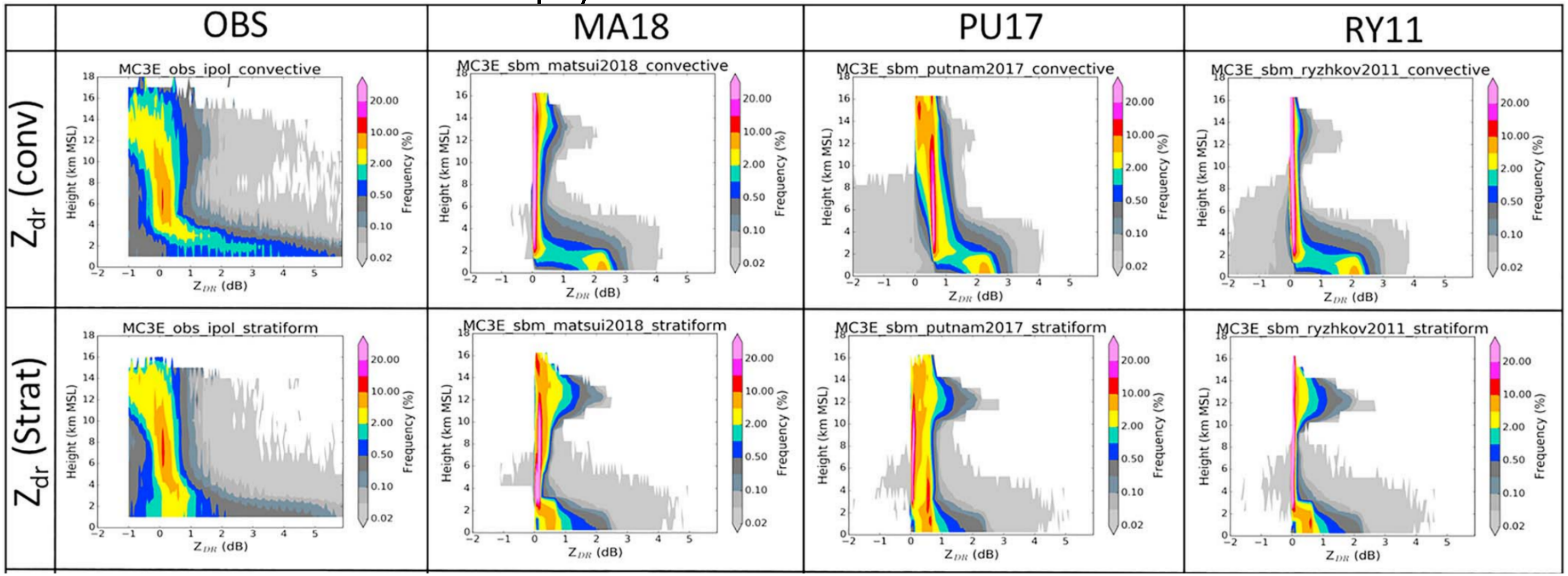
Augros et al. (2016), QJRMS

DGL signatures in other PFOs

SPP 2115

… consistent deficit in terms of **polarimetric response …**

MA18, PU17, and RY11 refer to *different shape and orientation assumptions* in the PFO for the precipitating frozen hydrometeors. Atmospheric state from WRF simulations using HUCM spectral bin microphysics is identical between the cases.



strongly oriented
graupel & hail

FO: POLARRIS
model: WRF-SBM

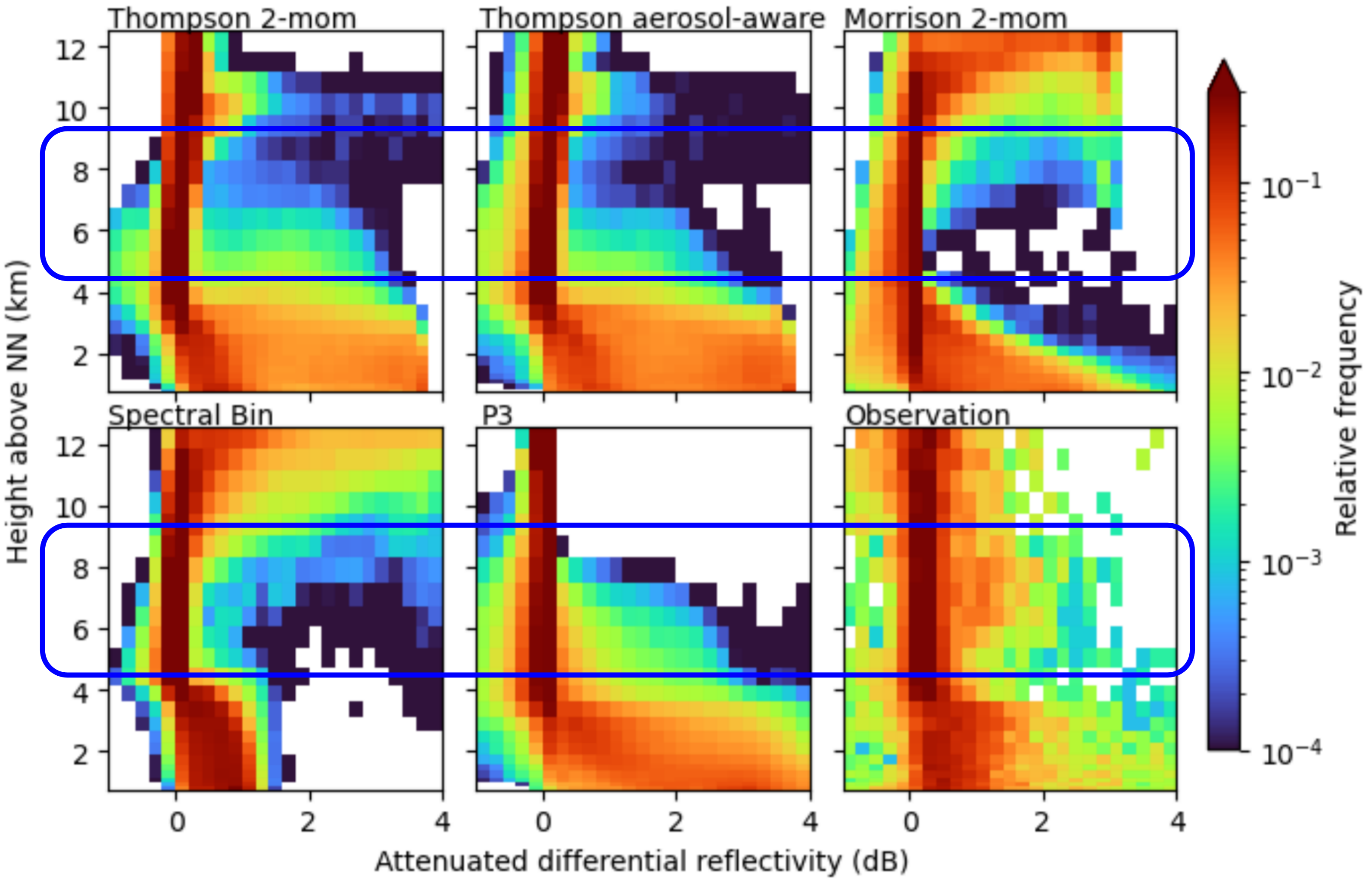
PRISTINE

Matsui et al. (2019), JGR

DGL signatures in other PFOs

PROM SPP 2115

... **consistent deficit** in terms of **polarimetric response** ...



FO: CR-SIM
model: WRF

Köcher et al. (2021), AMTD

DGL signatures in other PFOs

SPP 2115

... **consistent deficit** in terms of **polarimetric response** ...

There are **further explanations & reasons** for lack of polarimetric signals!

FO uncertainties that can contribute include, e.g.,
- melting models
- dielectric properties (primarily of air-ice(-water) mixtures)
- shape and orientation assumptions

Regarding **model microphysics** these include, e.g.,
- hydrometeor size distribution
- hydrometeor class partitioning
  - lack of secondary ice
  - wet growth processes
- mass-size relation
- mixed-phase hydrometeors

→ **Can we draw robust conclusions about model microphysics from synthetic signals based on homogeneous particle approaches?**