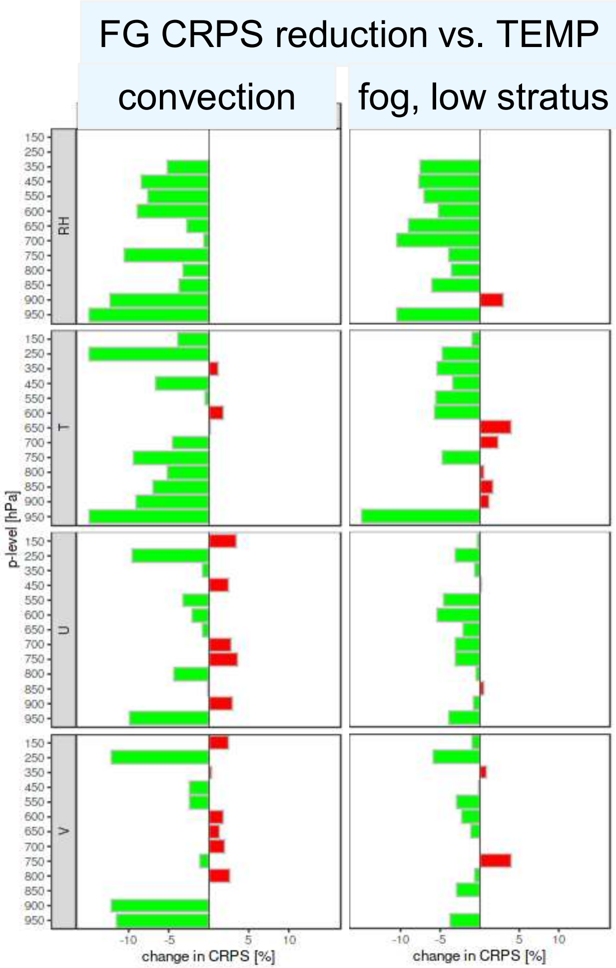
KENDAscope: KENDA from Surface to Cloud Observations Progressive Extension (Sept. 2020 – Aug. 2025)

- Task 1: algorithmic developments
  - 1.1 reference KENDA (currently LETKF): model parameter perturbations in DA; impact of Mode-S in ICON-global
  - 1.2 Variational DA (EnVar , CEnVar, 4D-EnVar)
  - 1.3 Particle Filter
- Task 2: observations (from surface to clouds)
  - 2.1 Radar (Z + Vr)
  - 2.2 ground-based GNSS ZTD + STD
  - 2.3 all-sky IR-WV + VIS radiances
  - 2.4 MTG IRS
  - 2.5 screen-level obs (T2M, RH2M)
  - 2.6 PBL profiling obs (wind lidar, MW radiometer, Raman lidar, drones, towers)
- Task 3: soil / surface (satellite soil moisture, SST, …)

MeteoSwiss *(Daniel Leuenberger, Bas Crezee, Claire Merker André Walser, Marco Arpagaus)*

- From COSMO to ICON + new HPC system: much technical work + testing
- LHN: ICON-D2 settings work well for ICON-CH, high precip intensities better than in COSMO
- EMVORADO in ICON: techn. ready for 5 Swiss radars, GPU port partly done and optimizations starting
- 2-week e-suites for 4 periods: convection, strong forcing, fog + low stratus in winter, strong diurnal cycle in spring
- KENDA-CH1 generally as good or better than KENDA-1 (except T2m, RH2m, 10-m bias)
- due to missing model perturbations, spread generally lower
- SPPT ready, beneficial (more than PP) for KENDA-CH1
- 2nd set of e-suites with improved ICON setup running SPPT, LHN, bug fix T_{soil}, SSO tuning, shallow-convection off



MeteoSwiss

ARPAE-EMR *(Thomas Gastaldo, Virginia Poli)*

- implementation of DA suite for ICON-I2 (to replace COSMO-2I in 2023)
  (ongoing due to some issue with the radar operator:)
- testing LHN (settings for ICON-D2 work well for ICON-I2)
- testing influence of initial soil moisture (IFS vs. ICON-EU) on 1-month summer period
- plan: operationalize ICON-I2 with LHN + KENDA w/o 3-D radar data (added later on)
- will work on satellite DA

CNMCA *(Francesca Marcucci, Valerio Cardinali)*

- maintenance of operational suite, migration to new ECMWF ATOS system
- tests with LHN + work on use of 3-D radar data in ICON
- plan to work on new satellite obs & soil moisture assimilation

Task 1.2: Variational DA (**EnVar**, **CEnVar**) for **deterministic** analyses / forecasts

Deutscher Wetterdienst DWD

(C)EnVar: runs technically in a preliminary version (for conventional obs with DACE obs operators that are used operationally in global DA)

- 2-week test EnVar (no-tuning) vs. 4D-LETKF (w. Synop, TEMP, aircraft obs): comparable
- much (!) work before operational (radar Z, VIS + WV cloud: extension of control vector)

CEnVar: no need to run LETKF (ensemble DA cycle) for deterministic analyses + forecasts
instead use pre-emptive coarse-scale ensemble to estimate required background errors B:

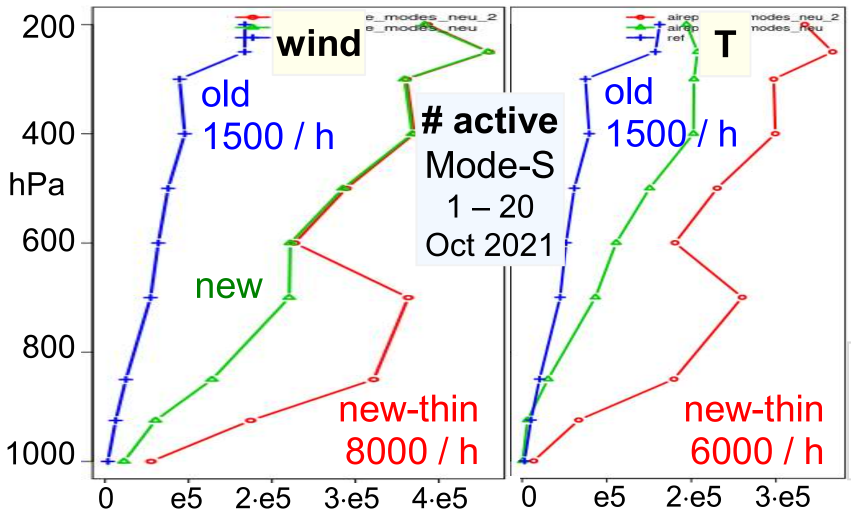
- CEnVar (with full ensemble B) technically ready:
  - with ensemble-B from complete or cropped ICON-EU or ICON-global ens. fields
- CEnVar (technical) test for Romanian NMA domain:
  - test at DWD: now works with obs set from DWD data base, and with obs (only Synop!) obtained from NMA
  - CEnVar ready for testing at NMA (technical test, then full performance tests, no resources so far)
- CEnVar for HMC (Brazil):
  - 6-day exp. at DWD: CEnVar vs. 3DVar (global clim. B) far better, vs. downscaler neutral
  - all single components function at HMC, setting up the DA job suite is ongoing

Task 1.1: Refinements on reference KENDA
'new' V2.2 Mode-S in ICON-D2

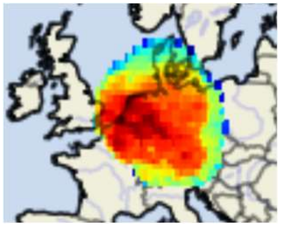
Deutscher Wetterdienst

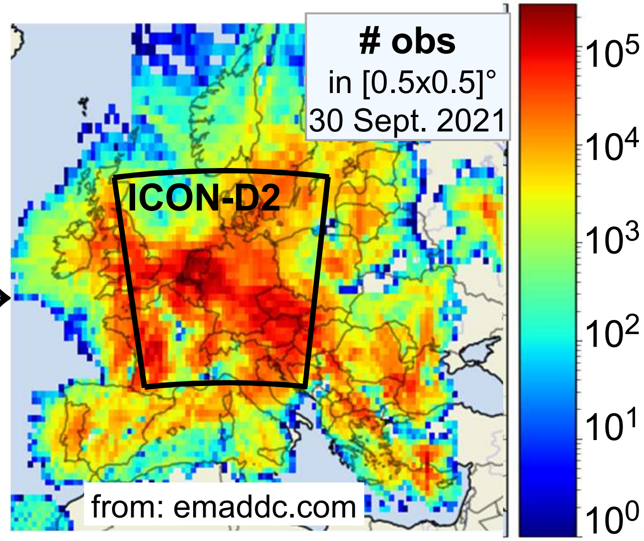
DWD

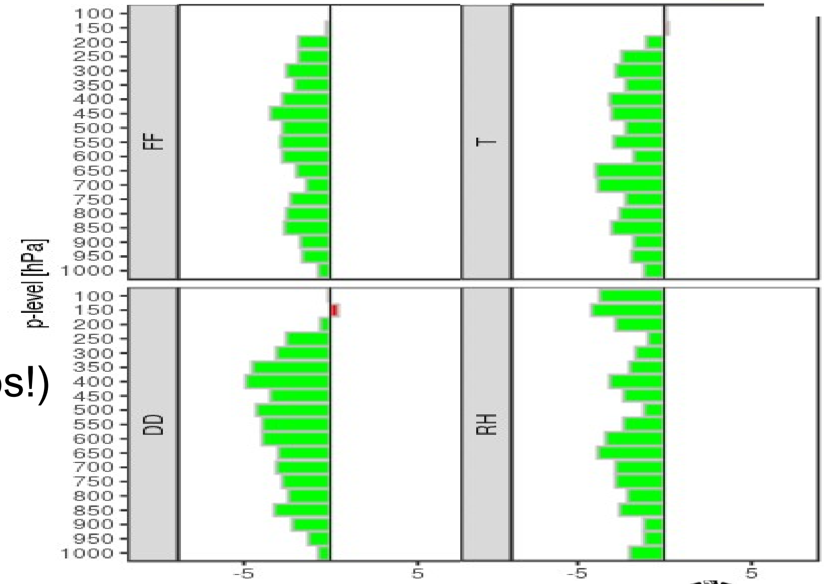
- Mode-S aircraft: processed + quality controlled by KNMI
  EMADDC: "European Meteorological Aircraft Derived Data Centre"
- new v2.2 Mode-S: operational in KENDA in March 2022
  ~ 45 / 25 million wind / T obs per day! (> 100 times more)



AMDAR:
1000 /h
each T, v







- rmse reduced by 3 – 4 % in upper air
  (also on humidity despite no additional humidity obs!)
- positive impact on precip + all var in Synop verif.
  reducing spin-down in clouds

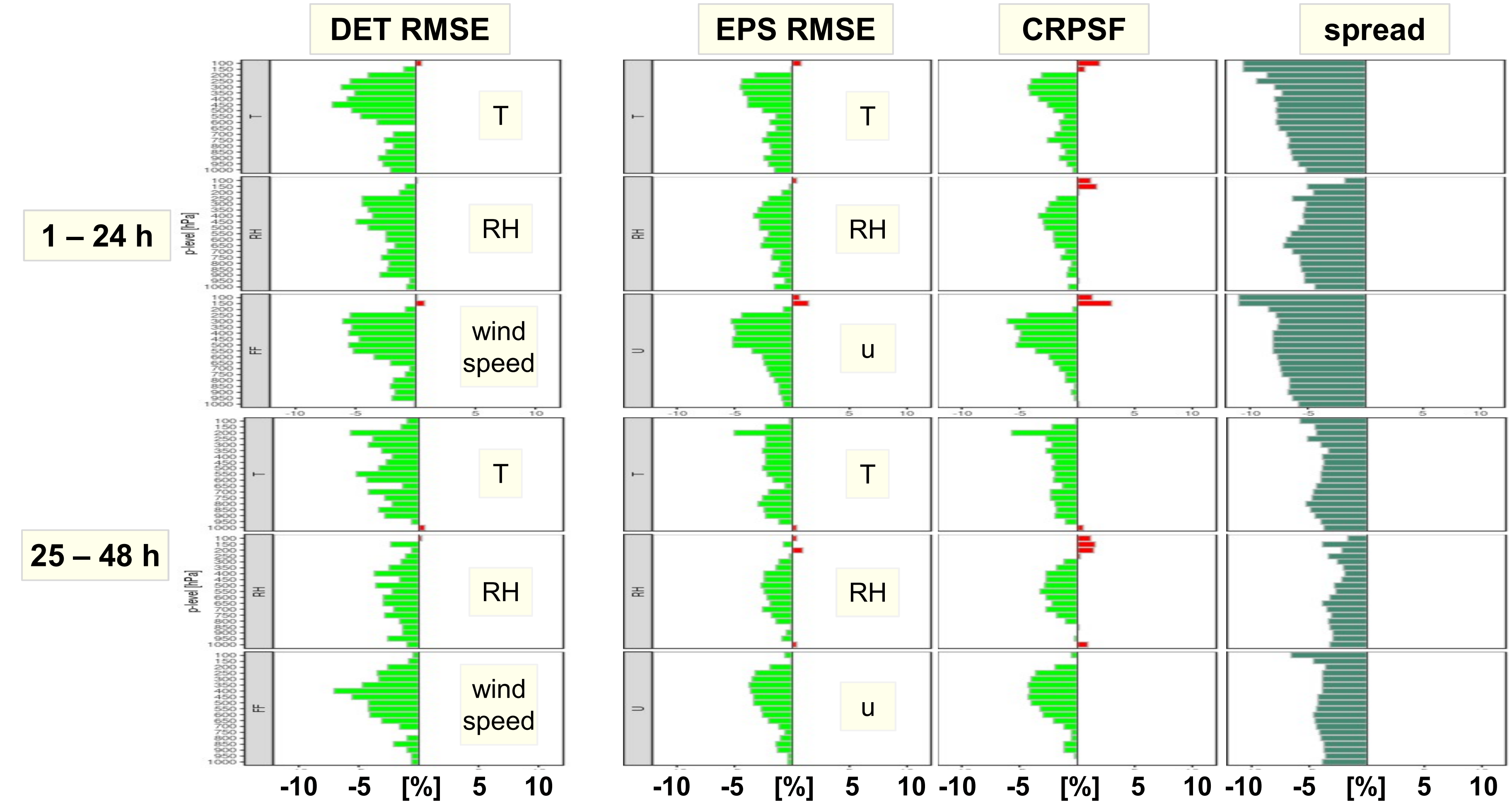
Impact of **adding Mode-S in global DA** (operational since May 2023) on ICON-D2

Deutscher Wetterdienst

DWD

radiosonde verif.

parallel suite April 2023



- very large + long-lasting reduction of errors + CRPS (2 – 6 %) and of spread (4 – 8 %)

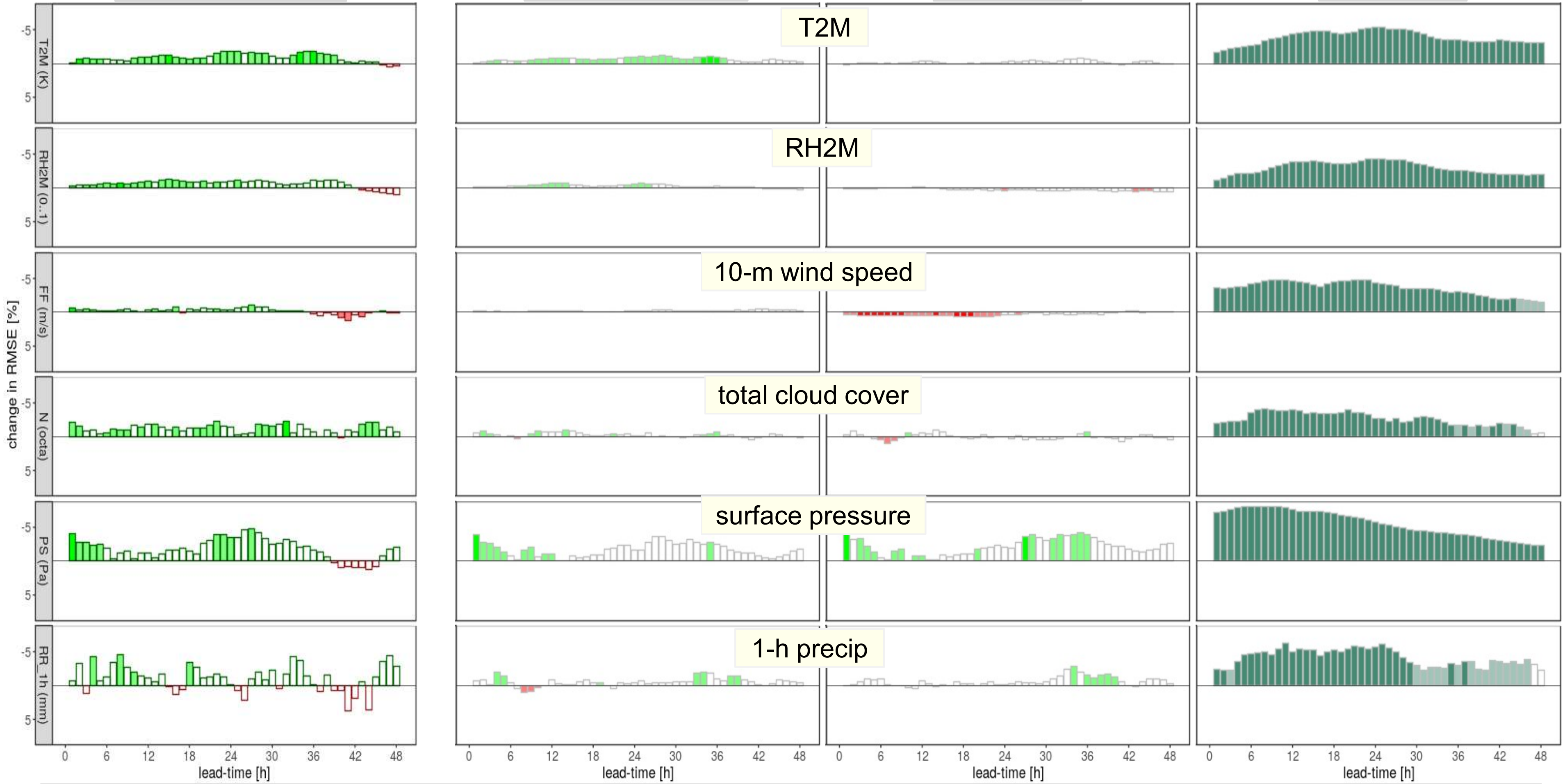
Impact of **adding Mode-S in global DA** on ICON-D2 via lateral BC

Deutscher Wetterdienst DWD

Synop verif.

parallel suite April 2023

DET RMSE | **EPS RMSE** | **CRPS** | **spread**



- errors reduced in det by 1 – 2 %; EPS spread reduced by 4 – 5 % !, spread/skill by 2 – 4 %

Ensemble Parameter perturbations in the KENDA assimilation cycle

(Klaus Stephan, Christoph Schraff, Hendrik Reich, Günther Zängl)

- ICON-D2-EPS: perturbation of physics parameters (PP), designed to increase spread particularly in PBL

- in DA cycle: PP settings as in global system
  - high consistency of perturbations between successive (1-h!) model runs in DA cycle, continuous range of perturbations instead of min./max. values
  - additional parameters, larger amplitudes for some

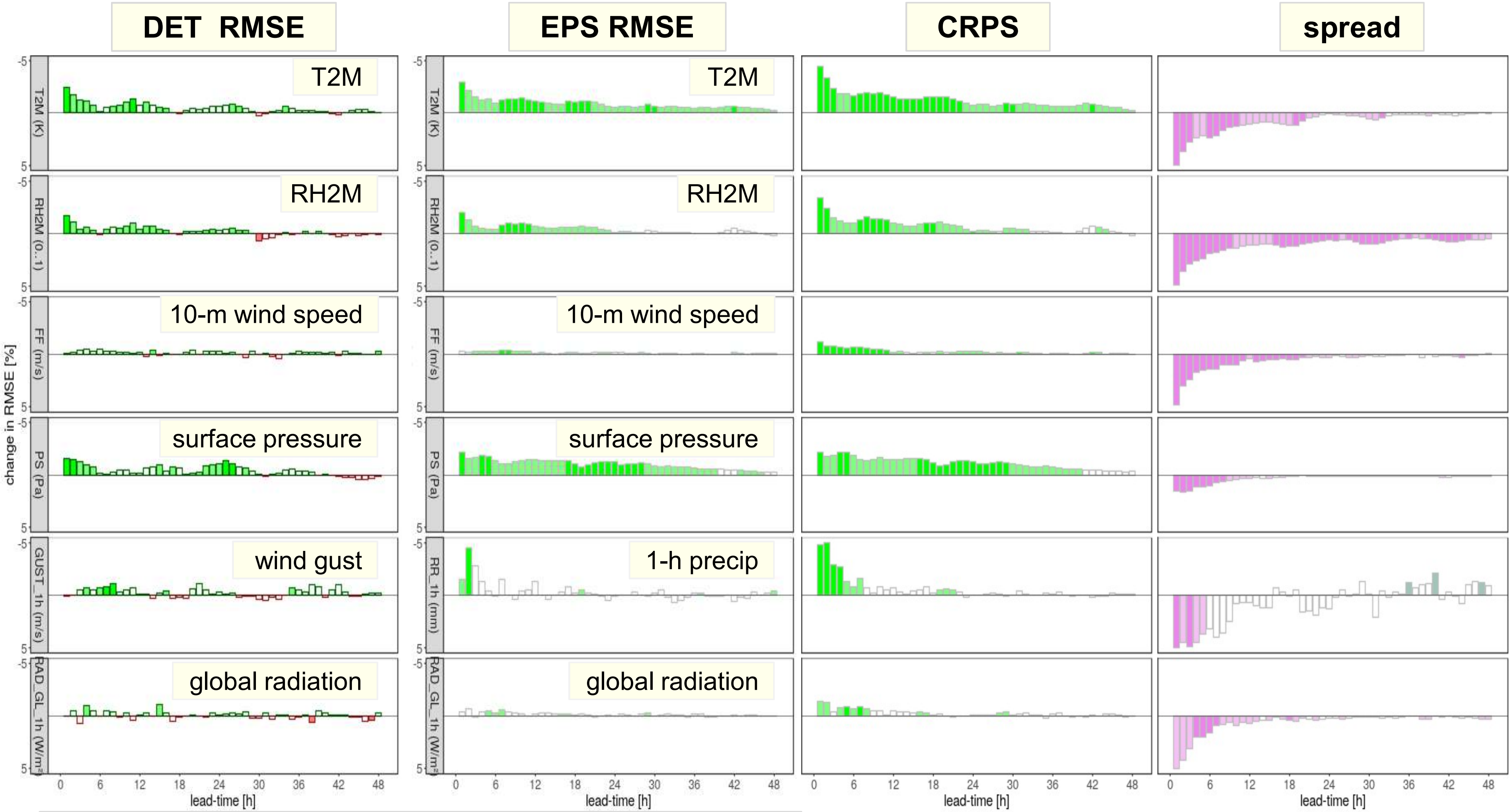
- in DA cycle: in addition perturbation of 4 latent heat nudging parameters (LHNP)
  - perturbing overall forcing, triggering of missing precip, ability to increase resp. decrease precip (i.e. bias)
  - influences directly only humidity field (after LHN retuning in 2022)

"Parameter Perturbations" in DA cycle:
Impact in parallel suite

Deutscher Wetterdienst

Synop verif.

2nd parallel suite 21/07 – 22/08/2023



- positive impact generally similar, up to +48 h conclusions

- PP:
  - reduces RMSE in T2M, RH2M, (ps) up to > 24 hrs
  - increases spread mainly in first 6 hrs
- LHNP:
  - reduces RMSE upper-air
  - spread increase larger + more long-lived
  - precip slightly improved (det. FSS 6 – 10 hrs; ens. BSS up to 24 hrs)
- together:
  - spread increase allows to assimilate ~15 % more radar reflectivity obs
  - RMSE error reduction 0.5 – 1% in DET + EPS in first 12 – 24 hrs
  - similar improvements for CRPS, spread (beyond 24 hrs)

- decision not to adapt of ICON-D2-EPS perturbation scheme accordingly
  (would require careful testing / evaluation , but resources very limited)
- parameter perturbations in DA cycle introduced in ICON-D2 parallel suite on 21/07/2023

  … and **operational** since 06/09/2023

Task 2.1: 3-D radar

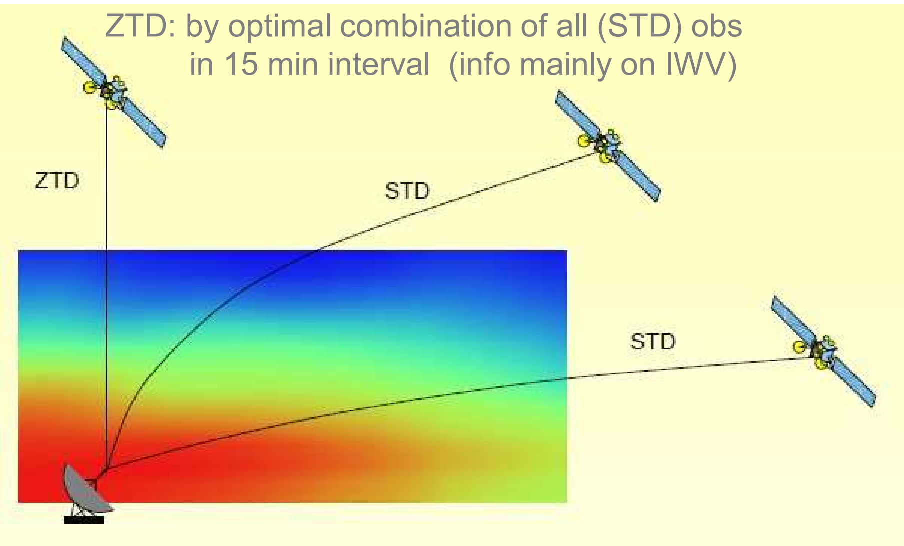
(Kobra Khosravian, Klaus Vobig, Lisa Neef, Klaus Stephan, Uli Blahak et al.)

- reflectivity: testing targeted covariance inflation:
  in areas with missing (insufficient) precip / spread → only new cells
- use of foreign radars : successful tests with French radars

  technically, 47 foreign radars (NL, BE, FR, CH, POL, CZ, DK) ready for operational use
  (reflectivity: all radars, radial velocity only partly (DK good, F, NL not so good))
  but need to specify / tune selection of elevation from each country (very heterogeous)
- WG1: assimilation of radar-derived objects / lightning / nowcast cell features / FSS (ongoing)
- WG1: use of dual-polarization moments (direct / hydrometeor mixing ratio retrieval)
- WG1: Assimilation of Commercial Microwave Link data (CML are affected by attenuation, which can be calculated by EMVORADO; first experiments started)
- 2-moment microphysics: model 'tuning' for improved precip, investigation of spin-up (LHN)
- LHN of nowcasting radar composites: impact negative

Task 2.2: ground-based GNSS Zenith / Slant Total Delay *(Michael Bender)*

- first ICON-D2 experiments (June + July 2021 : old Mode-S, no SEVIRI VIS):
  - **no-GPS**: reference (no GNSS)
  - **ZTD**: (GPS-derived) ZTD only
  - **STD+ZTD**: ZTD + GPS-derived STD (low elevations < 25 deg only)
  - ZTD + GNSS-derived STD (2.5 * more STD's, incl. Galilei, Glonass)



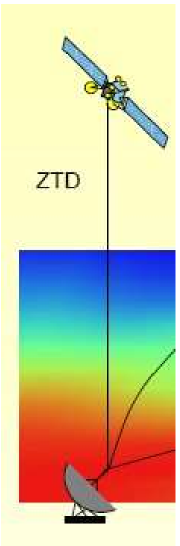
Ground-based GNSS (GPS) ZTD + STD

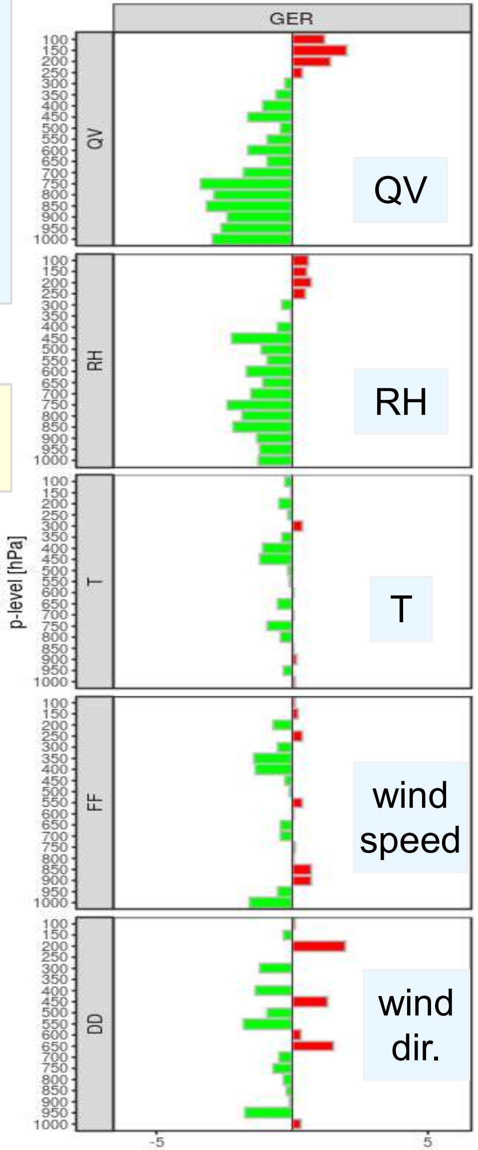
Deutscher Wetterdienst

07.06. – 31.07.2021

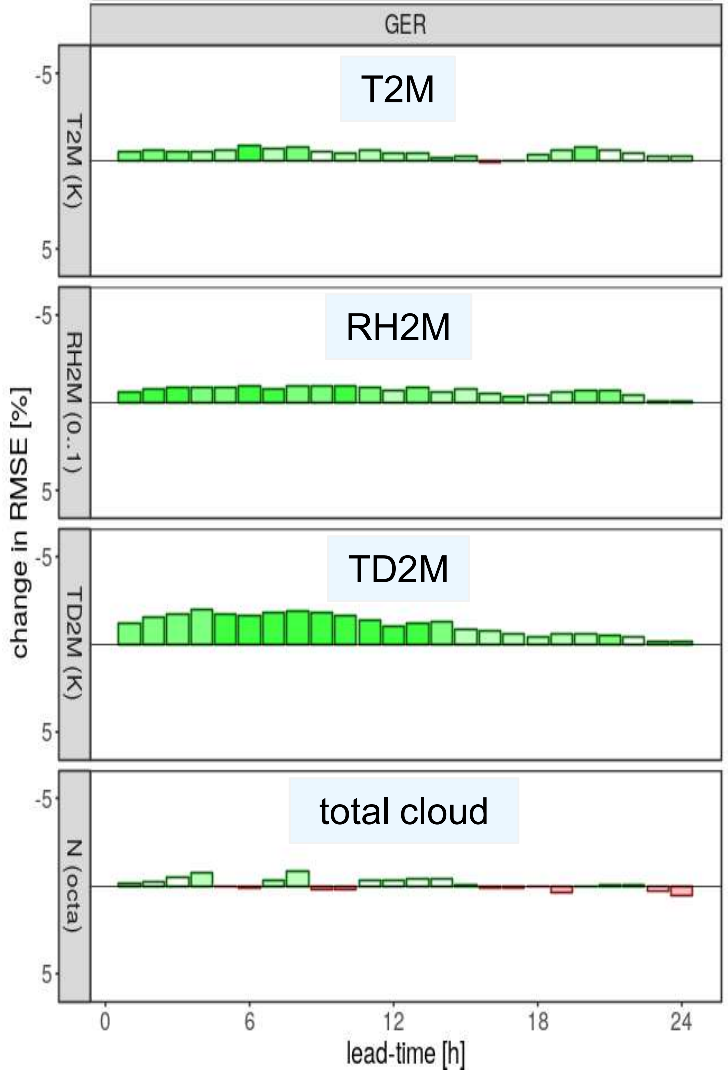
ZTD vs. no-GPS: change [%] of RMSE vs. radiosondes (Germany)
averaged over 1 – **12 h**, 0, 6, 12, 18 UTC runs

ZTD better
no-GPS better





RMSE vs. Synop (Germany)



Ground-based GNSS ZTD + STD

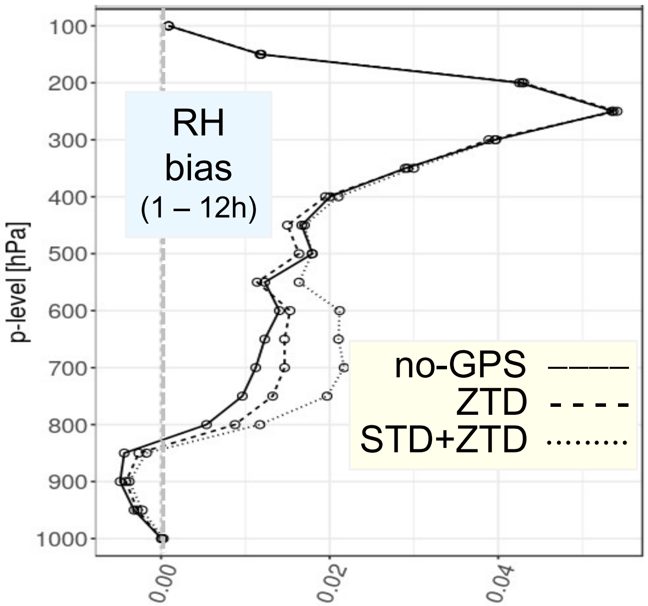
Deutscher Wetterdienst

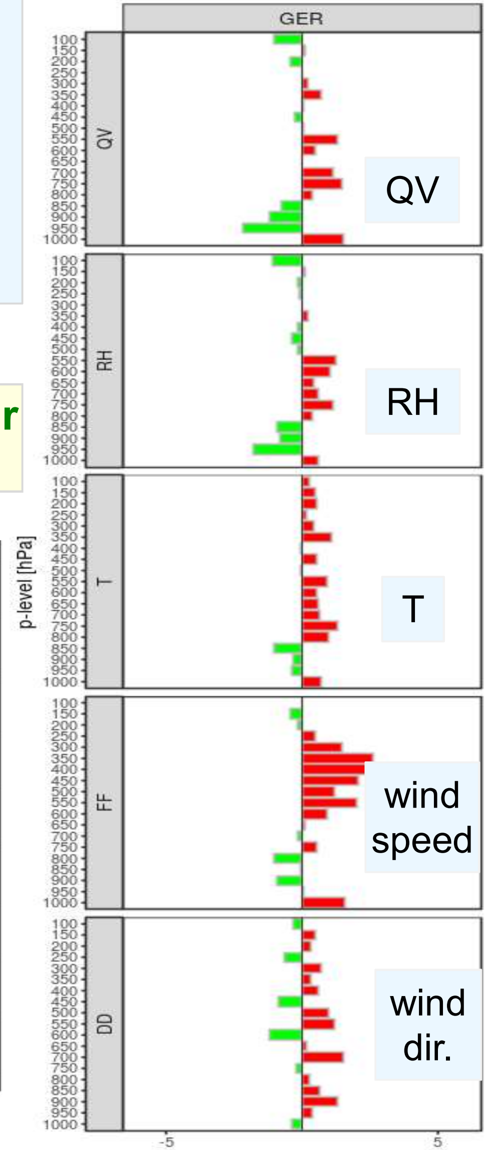
DWD

STD+ZTD vs. ZTD: change [%] of RMSE vs. radiosondes (Germany) averaged over 1 – **12 h**, 0, 6, 12, 18 UTC runs

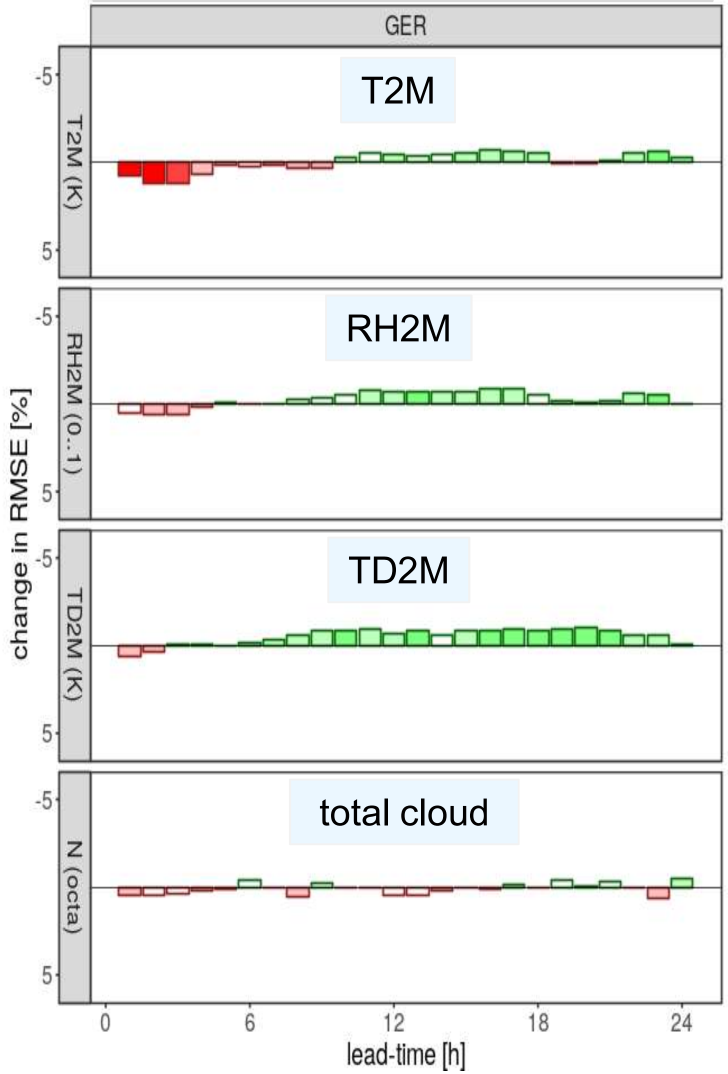
07.06. – 31.07.2021

STD+ZTD better
ZTD better





RMSE vs. Synop (Germany)



Ground-based GNSS (GPS) ZTD + STD

Deutscher Wetterdienst

- **ZTD** impact: clearly positive for humidity (RH2M, 2 % error reduction up to 700 hPa)
  very slightly positive for temperature (incl. T2M)
  ~ neutral for wind, precip, cloud, etc. (no show-stopper)
- additional low-elevation **STD**: small impact,
  slightly negative for upper-air wind + temperature, slightly positive for precip

Next steps:

- further impact experiments, with operational use of obs: SEVIRI VIS + WV, new Mode-S
  - winter experiment: very slight (positive) impact
  - new summer experiment (June 2023) started
- possible procedure: operationalize ZTD first, improve STD assimilation in parallel
  → work on: obs error variances (adaptive, station dependent, using GPS processing info),
  bias correction (elevation + azimuth bins)
  localization (info from FSOI tool), possibly obs error correlations

Task 2.3: all-sky (cloudy) IR + VIS SEVIRI radiances

- **VIS** channels: info on all clouds, incl. low clouds (but not on cloud top height) at daytime

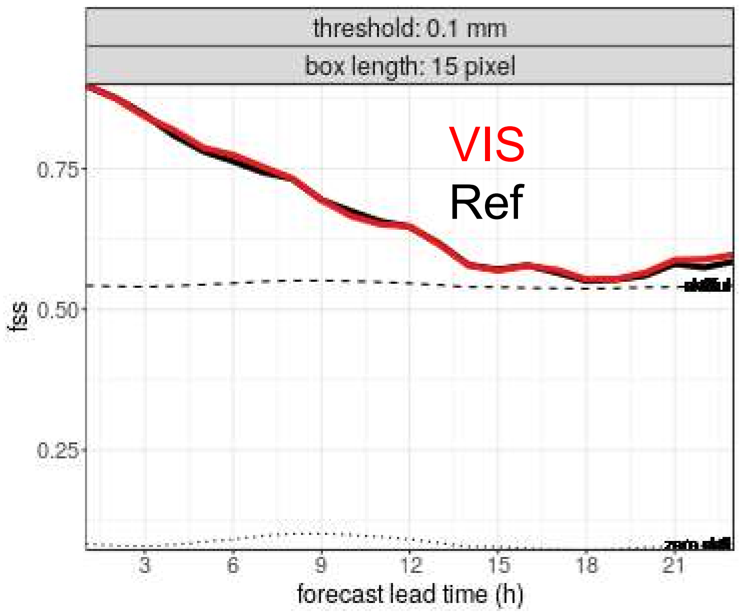
  (Lilo Bach et al.)

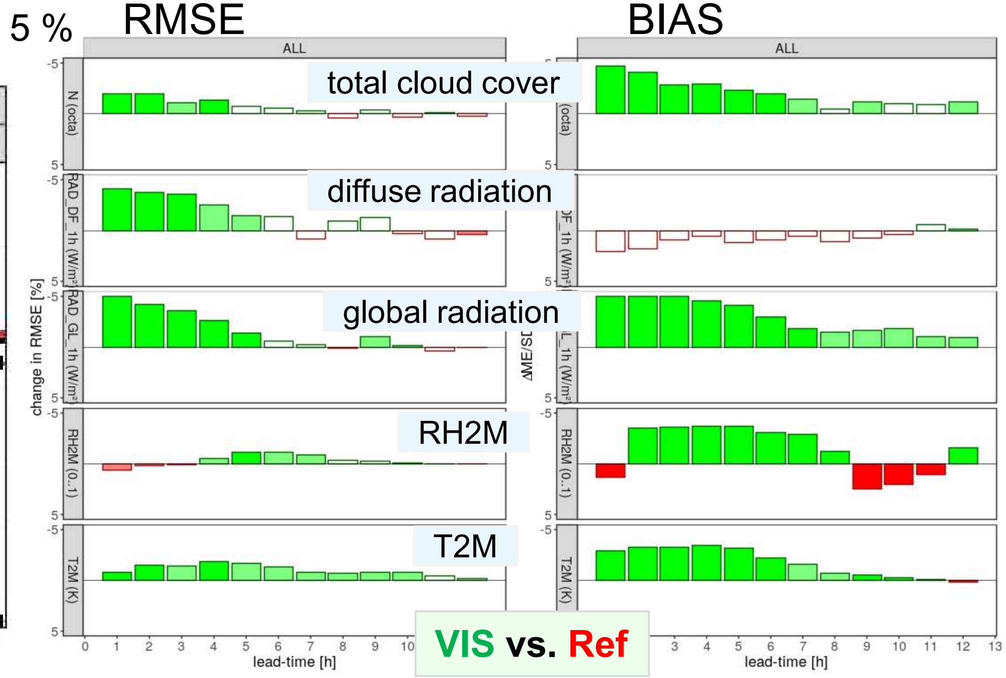
  – latest experiment, ICON with LH of sub-grid cloud condensation, 12.05 – 11.06.2022

  – positive impact on cloud, radiation, 2-m temperature + humidity; upper-air neutral

  – precip neutral, no increase of negative bias

FSS vs. RADAR





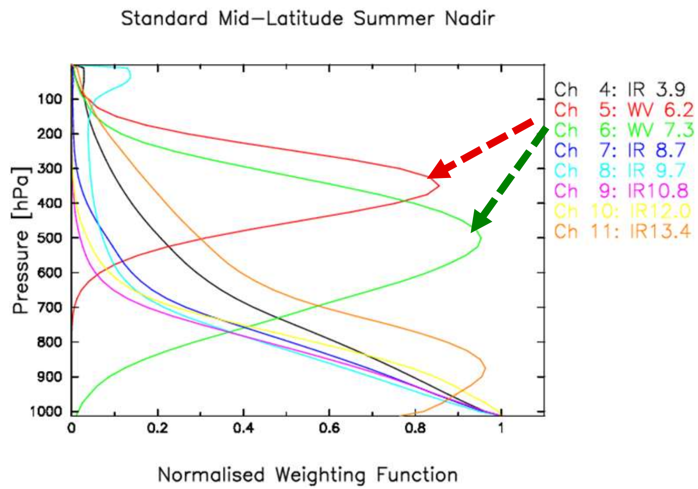
All-sky (cloudy) SEVIRI VIS

- **VIS** channels: info on all clouds, incl. low clouds (but not on cloud top height) at daytime
  (Lilo Bach et al.)
  - in Sinfony-RUC since Oct. 2022
  - monitoring of SEVIRI VIS set up in global DA system (in NUMEX exp. for time being)

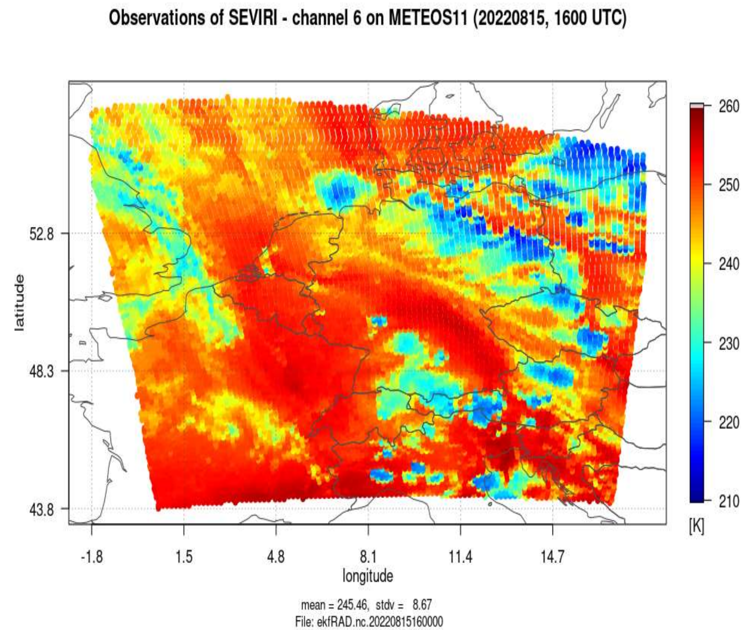
- **operational** since 15 March 2023:
  - ✓ **first time in KENDA**: use of **satellite** data (except clear-sky rad. at CNMCA)
  - ✓ first time at **DWD**: use of **cloudy** satellite data
  - ✓ first time **internationally**: use of **visible** channel data

Task 2: Observations (surface to clouds)

- **IR WV** (water vapour) channels: info on WV + **clouds** in mid- to upper troposphere
  (Annika Schomburg et al.)



- what has been tested:
  - different obs error models
    (constant error, error model with different inflation)
  - different height assignment methods
    (based on Jacobians and transmission)
  - vertical localization (0.3 vs 0.25 (vs. 0.15))
  - horizontal localizations (35km, 25km, 12.5km)
  - superobbing, different thinning distances
  - with and without QI update
  - without and in **combination with SEVIRI VIS !**
    → revised VIS settings, e.g. vert. loc. at 800 hPa
  - periods: June, Aug – Sept, Nov., Feb.



All-sky SEVIRI IR WV

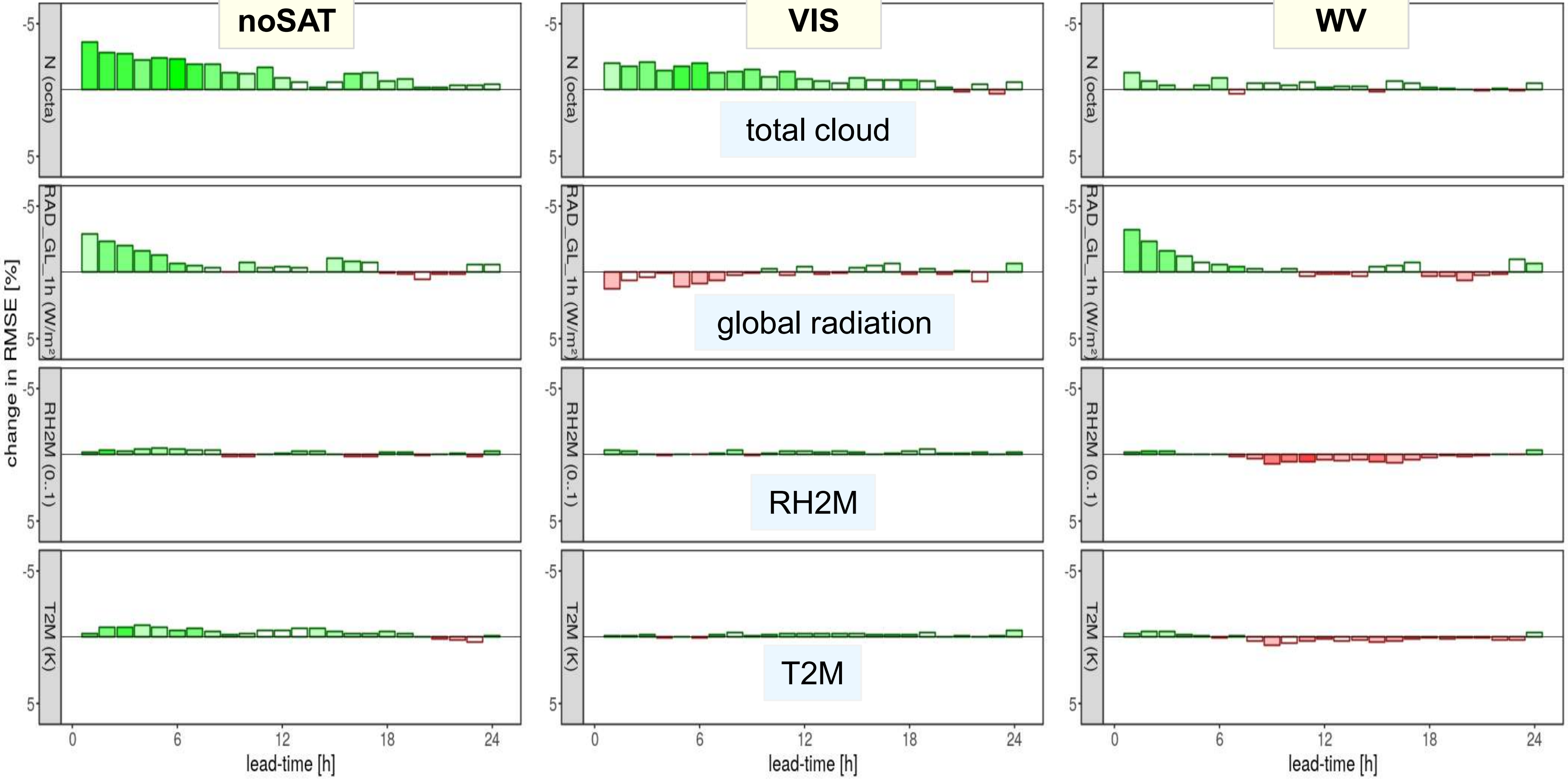
WV+VIS vs. **noSAT**

15 Aug. – 12 Sept. 2022 (incl. new Mode-S)

WV+VIS vs. **VIS**

0-, 6-, 12-, 18- UTC runs

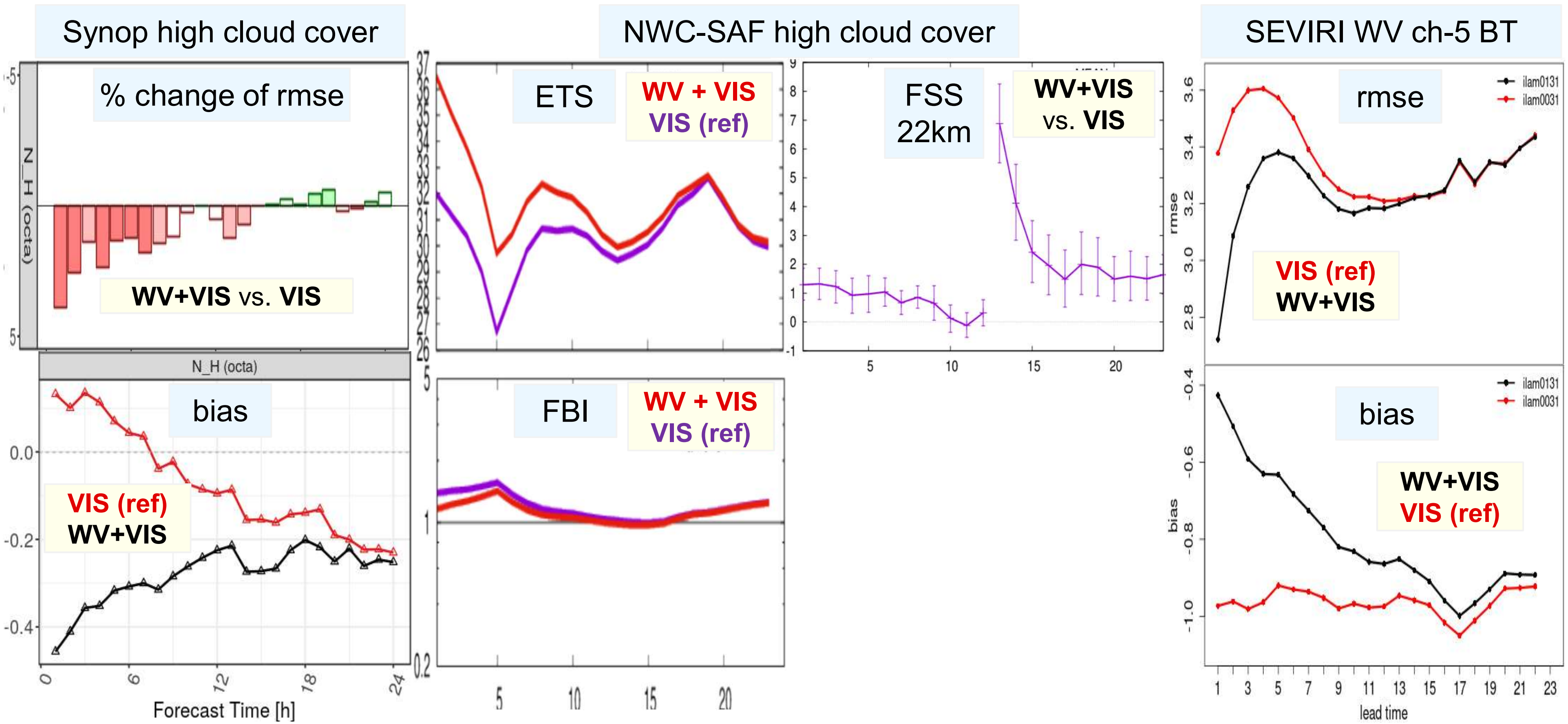
WV+VIS vs. **WV**



– extra benefit VIS: surface radiation

– extra benefit WV: upper-level QV + total cloud cover (high cloud slightly worse in new exp.)

All-sky SEVIRI IR WV



- Synop high cloud: WV introduce underestimation of high cloud, negative impact
- Satellite-derived NWC-SAF high cloud, SEVIRI brightness temperature (ch5 + ch6): WV reduce overestimation of high cloud, clear significant positive impact

All-sky SEVIRI IR WV

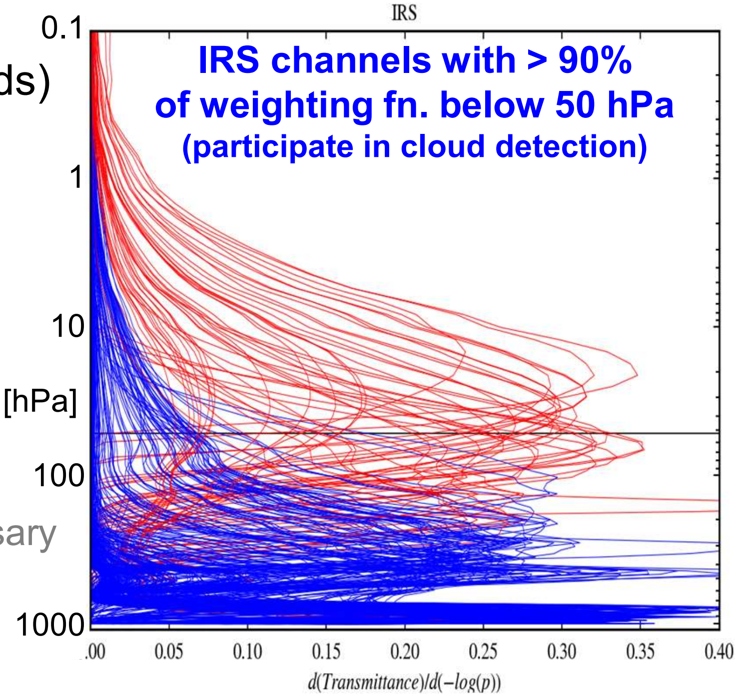
- SEVIRI WV channels: summary
  - suitable settings for combined use of WV + VIS data found, results in BACY exp. ok, positive impact of adding WV on cloud + upper-tropospheric humidity, underestimation of convective precip slightly decreased (12-UTC runs)
  - NUMEX experiments with current oper. NWP environment (Mode-S in global/EU LBC) started for summer and winter periods
  - if results ok, SEVIRI WV can be introduced / tested in parallel suite

- further steps VIS + WV channels
  - preparation for VIS & WV of FCI @MTG
  - further visible + near IR channels

Task 2.4: **MTG IRS** (Meteosat Third Gen. hyperspectral IR Sounder, launch mid-2024)

(Mahdiyeh Mousavi, Christina Köpken-Watts, a.o. DWD)

- temperature + humidity profiles (clear-sky / above clouds)
- simulated IRS ‚obs' (with RadSim) into fdbk file
- (evaluating) skin temperature T_s retrieval from very low peaking channels, then use T_s for assimilated channels (in LETKF);
  land IR-emissivity Atlas implemented (monitoring)
- (improving) cloud detection (ICON-global + ILAM):
  extrapol. above ILAM model top with global fields found necessary
- channel selection (generic tool based on DFS)



- LETKF code being extended for use of non-diagonal obs error covariance matrix $\mathbf{R}$ with inter-channel correlations (→ *Steffi Hollborn* + *Hendrik Reich*, requires distributed obs process.)

… before meaningful assimilation experiments can start

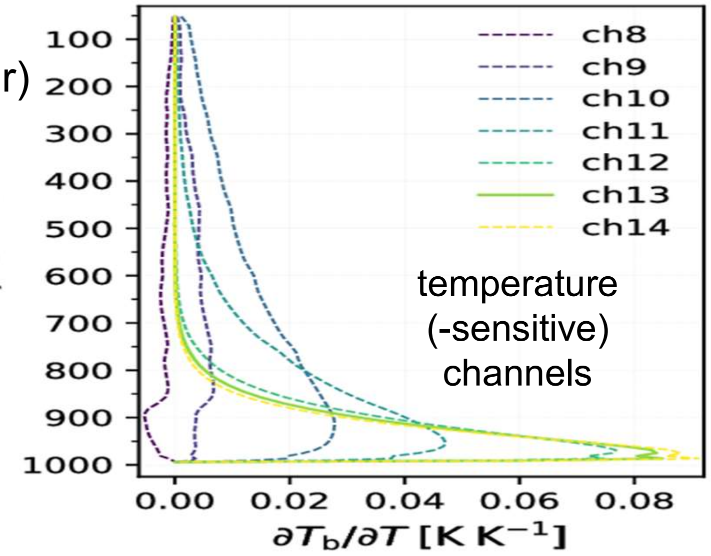
- important aspects: slant radiative transfer, 4D-EnVar (for indirect wind info),
  horizontal obs error correlations (for use of obs at high resolution)

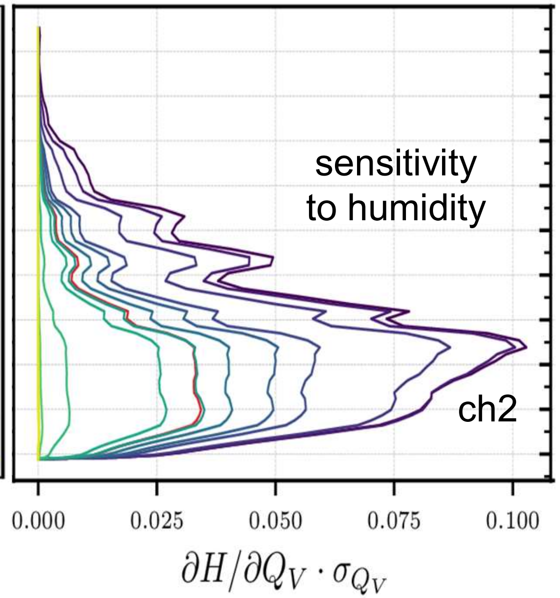
MWR (Microwave radiometer)

(Jasmin Vural; Annika Schomburg, Christoph Schraff)

characteristics of MWR at Lindenberg

- sensitivity of channels in DA



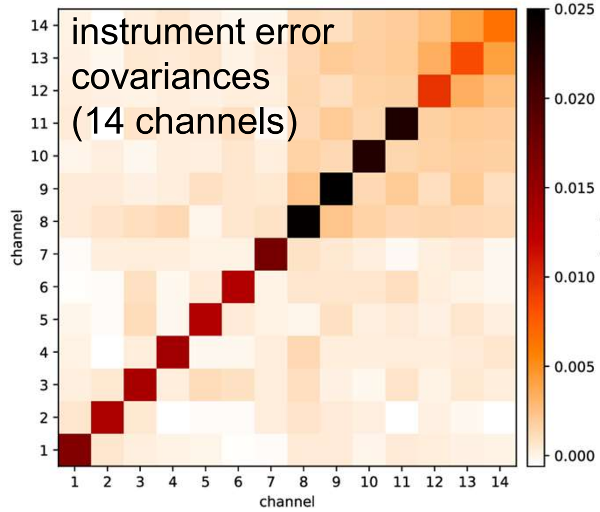


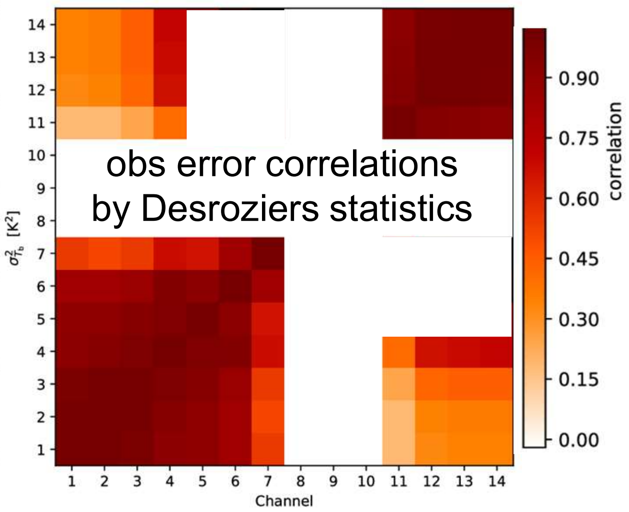
interchannel error correlations

- from instrument only: small
- total (incl. representativeness, observation operator) : very large !!

→ DWD: use only chann. 2, 13 (good O – B stats)

→ (MeteoSwiss: 10 channels oper. w. large specified obs errors)



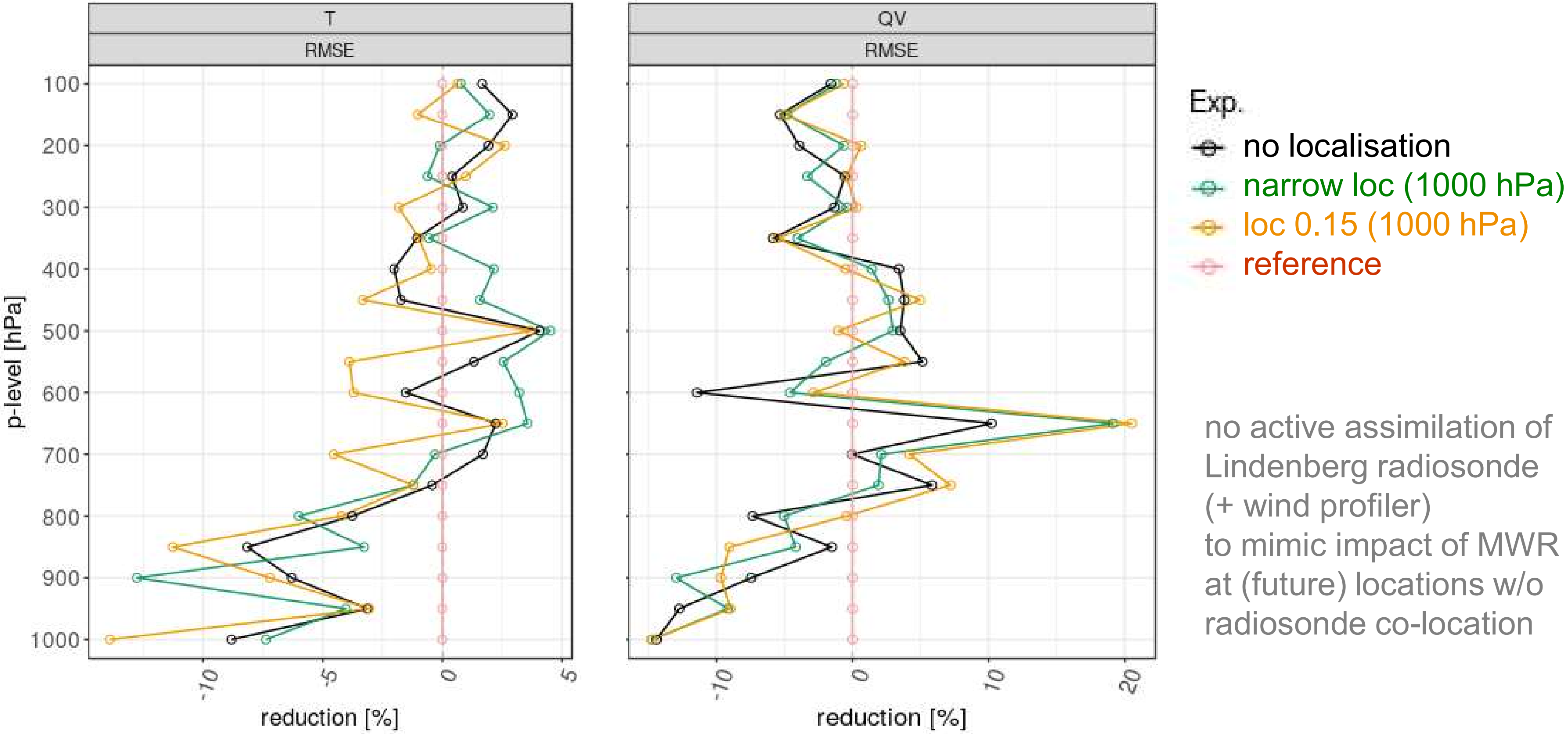


Assimilation of MW radiometer data

Deutscher Wetterdienst

change [%] of RMSE against **Lindenberg** radiosonde
June 2021, averaged over 1 – 6 h, (mainly **+ 5 h**),
0-, 6-, 12-, 18- UTC runs

temperature
channel 13



no active assimilation of Lindenberg radiosonde (+ wind profiler) to mimic impact of MWR at (future) locations w/o radiosonde co-location

- vertical localisation: secondary effect, inconclusive results
- all exp.: T ≥ 800 hPa , QV ≥ 850 hPa improved; QV 650 hPa degraded ? … against 1 ref !

Assimilation of MW radiometer data

Deutscher Wetterdienst

change [%] of RMSE against **Lindenberg** radiosonde
June 2021, averaged over 1 – 6 h, (mainly **+ 5 h**),
0-, 6-, 12-, 18- UTC runs

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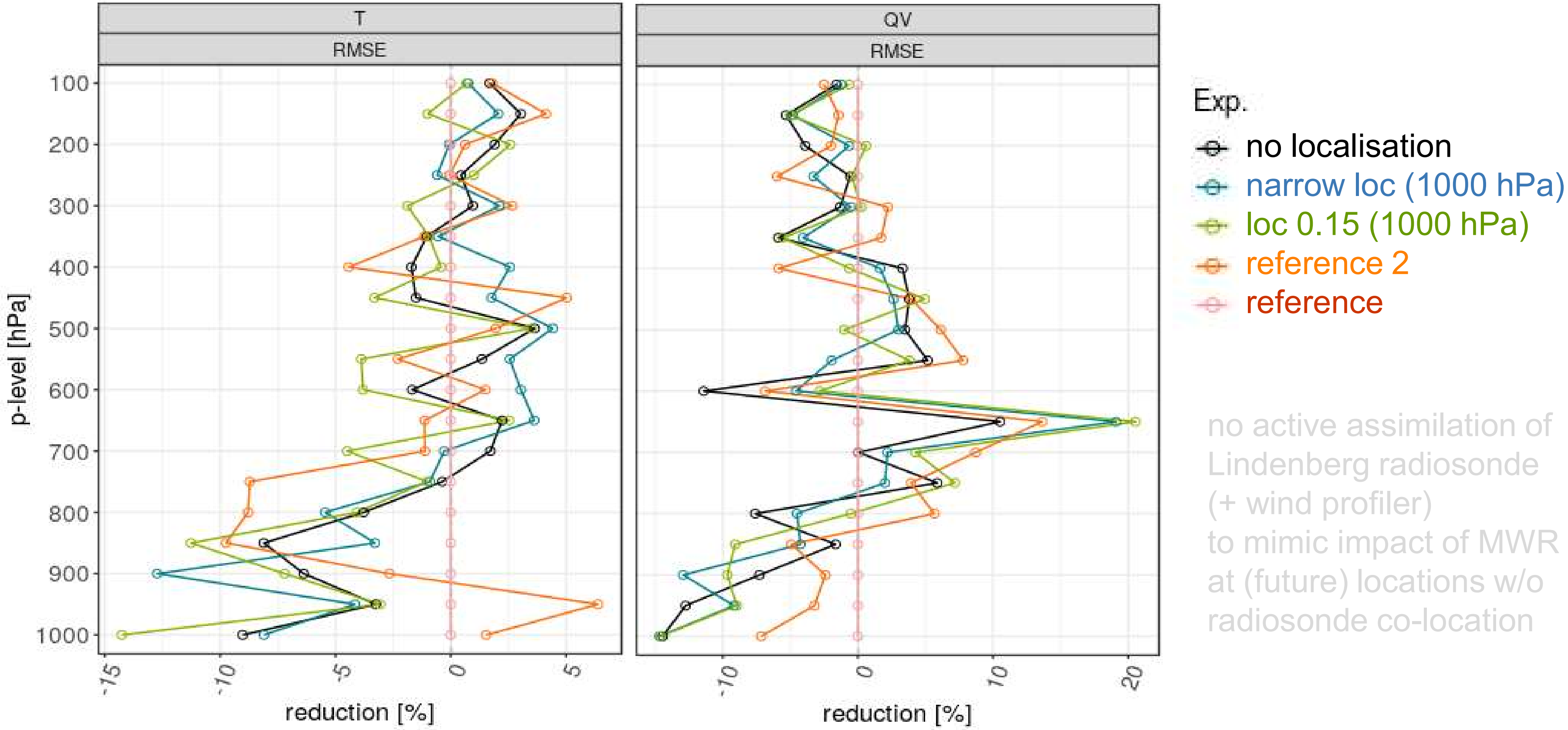


no active assimilation of Lindenberg radiosonde (+ wind profiler) to mimic impact of MWR at (future) locations w/o radiosonde co-location

- vertical localisation: secondary effect, inconclusive results
- all exp., 2 refs: T ≥ 900 hPa , QV ≥ 900 hPa improved

Assimilation of MW radiometer data from a **single station**: **lessons learnt**

Deutscher Wetterdienst

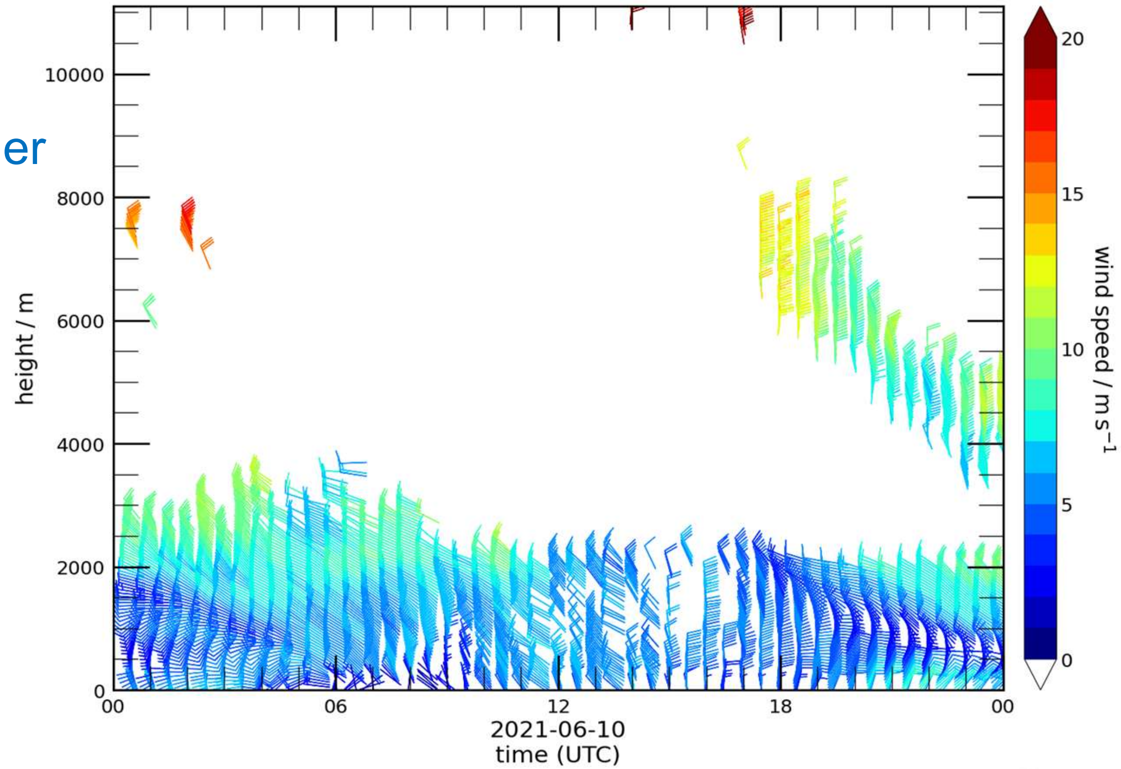
DWD

- only 1 (or few) instruments: difficult to obtain conclusive (significant) results
  - Rfdbk: info on (lack of) statistical significance only for separate initial times
  - learning exercise for us (initially individual exp. given too much creditability)
  - are results confirmed in similar experiments?
  - also depends on available verifying obs in immediate vicinity
- only very coarse tuning possible,
  finer tuning experiments inconclusive, not possible to tune vertical localization
- many experiments with positive impact in lowest 100 – 200 hPa with channel 2
- inter-channel error correlations $\rightarrow$ full $\mathbf{R}$-matrix in LETKF
- more stations, better reference obs (Raman lidar?) needed

wind lidar (at Lindenberg) *(Jasmin Vural; Annika Schomburg, Christoph Schraff)*

Characteristics of wind lidar data at Lindenberg

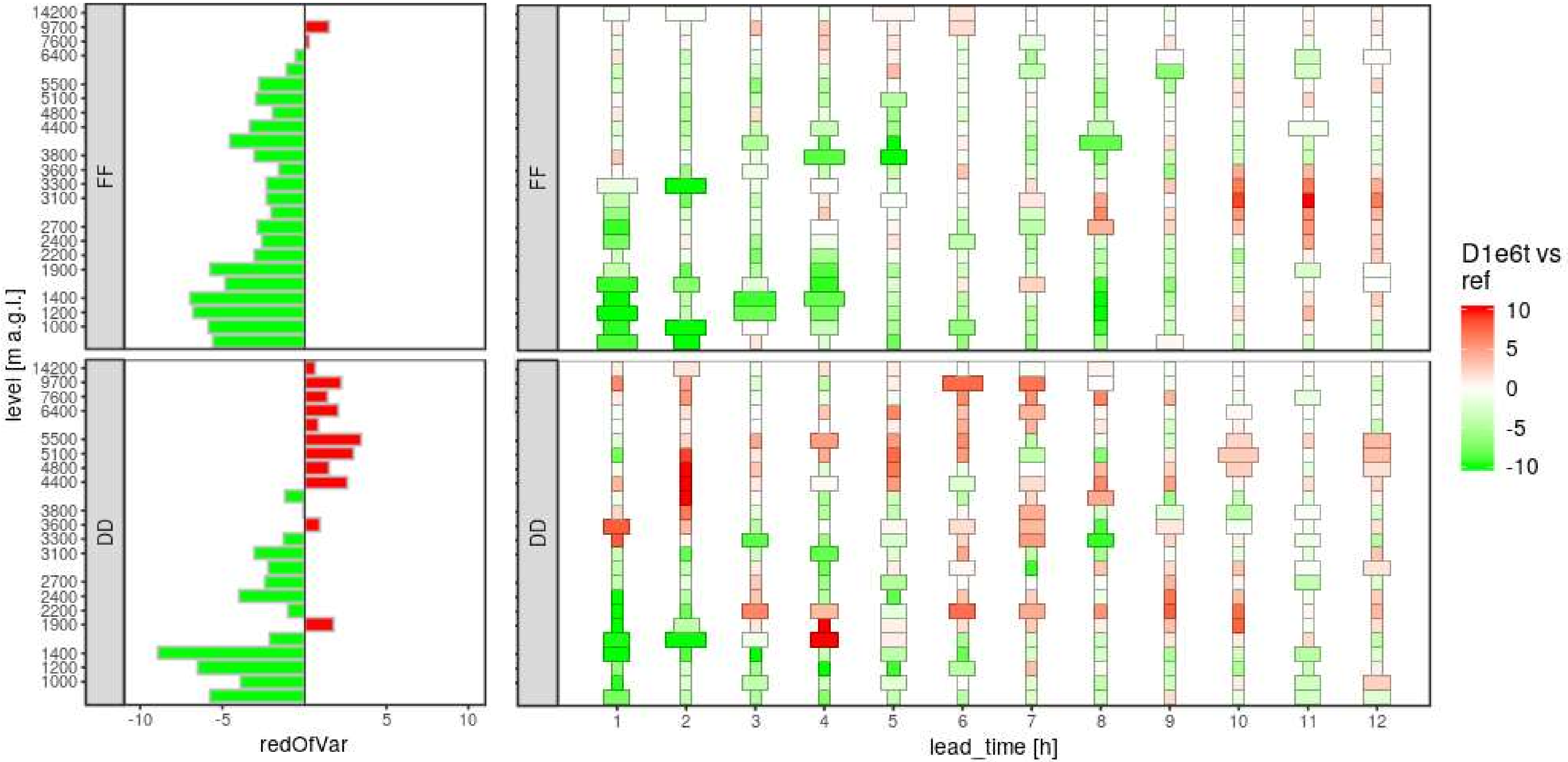
- assimilation 1 obs profile per hour
- vertical resolution 50 m; thinning optionally (100 m (below 3000 m) resp. 150 (above))
- obs error tuning
- verif. against 1-hrly wind profiler



Assimilation of wind lidar data

change of RMSE against Lindenberg wind profiler, 15 May – 30 June 2021, 0-, 6-, 12-, 18- UTC runs

averaged over 1 – 6 h



Assimilation of wind lidar data

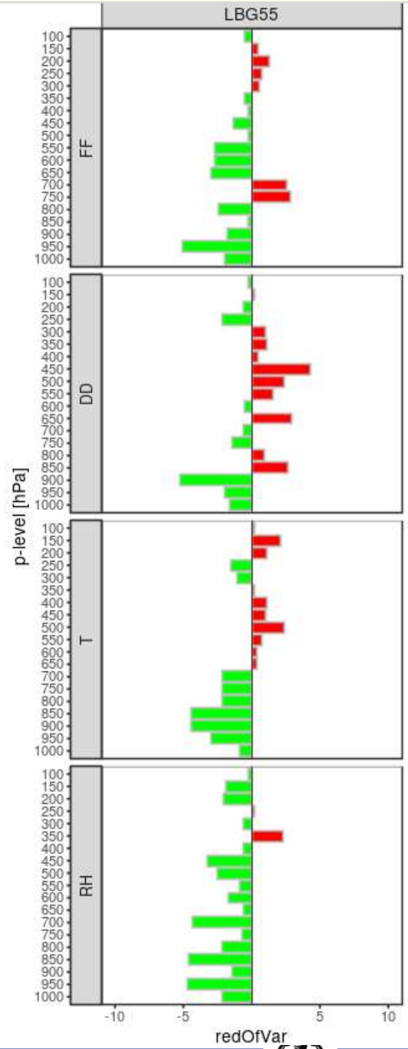
Deutscher Wetterdienst

- May – June 2021 period, summary:
  - up to 5 % error reduction of wind speed (direction) below 5 km (1.5 km) @ Lindenberg (in several experiments)
  - positive impact on T, RH below 700 hPa (some exp.)
  - neutral / inconclusive impact in Synop / Airep verif.
  - tuning of thinning / obs error specif. often inconclusive

- latest experiments 15 Aug. – 15 Sept 2022:
  - 1 – 2 % error red. of wind, (T, RH) < 3 km @ Lindenberg (?), but general impact neutral / inconclusive
  - possible reasons:
    - more (wind) obs in ref: radar (radial winds), new Mode-S
    - different period

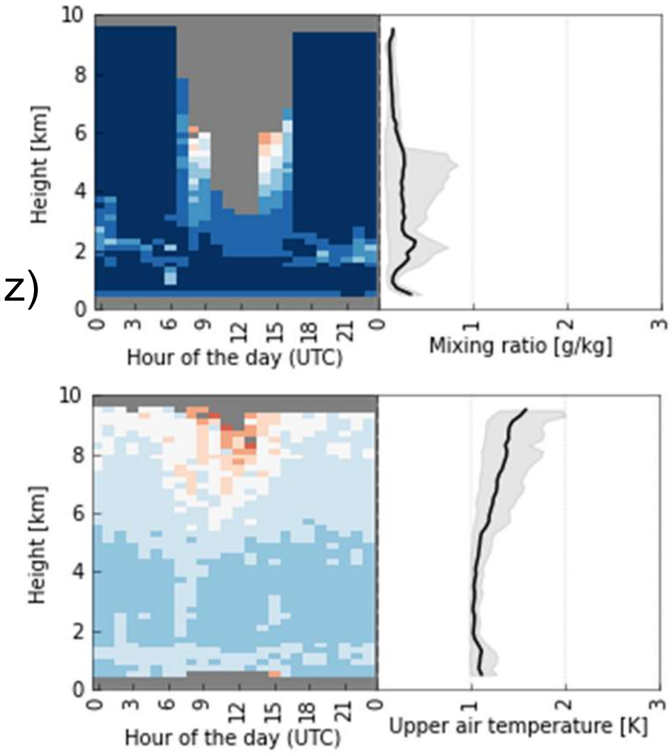
- by end 2023: 6 wind lidar stations in DE

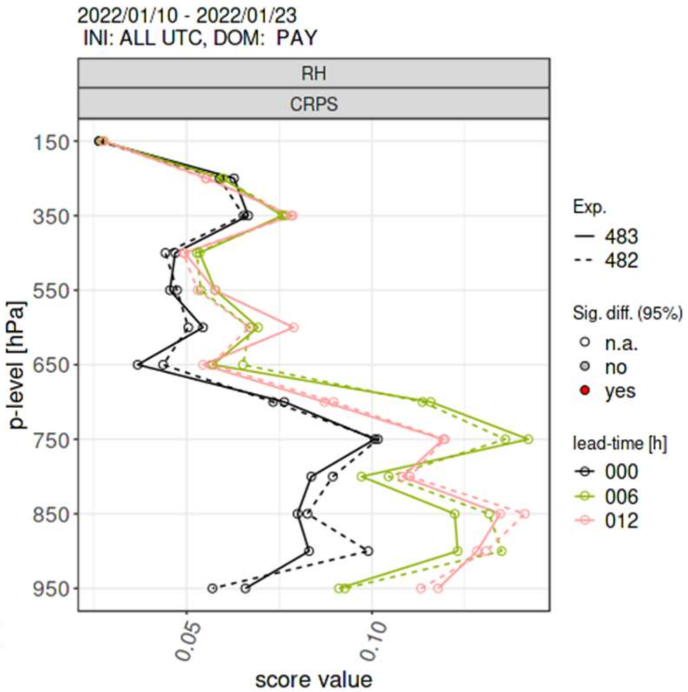
15 May – 30 June 2021
averaged over 1 – 12 h



Assimilation of Raman Lidar Observations

- new experiments with improved obs quality
- state-dependent observation error:
  - MIXR: $e\_o(t,z) = e\_o_{instrument}(t,z) + 0.03 * MIXR\_clim(t,z)$
  - T: $e\_o(t,z) = e\_o_{instrument}(t,z) + 0.5\ K$





improvements in obs quality lead to slight benefit of Raman lidar obs on KENDA-1 DA cycle + forecasts

- radiosonde: RH, T up to +6h at Payerne
- Synop: RH2m, cloud cover
- satellite verif: fog & low stratus (first hours)