

TKESV Turbulence Scheme within ICON: Implementation Details and Some Possibly Useful Hints

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- Motivation: why is a step beyond algebraic and one-equation TKE schemes needed?
- TKESV scheme, key features
- Implementation into ICON
- Some results from test runs
- Configuration, tuning, a few hints
- Work in progress, outlook

Motivation (recall)

A step beyond algebraic and one-equation TKE schemes
(draft horses of geophysical turbulence modelling)

$\langle u_i'^2 \rangle$ – kinetic energy of SGS motions (TKE)

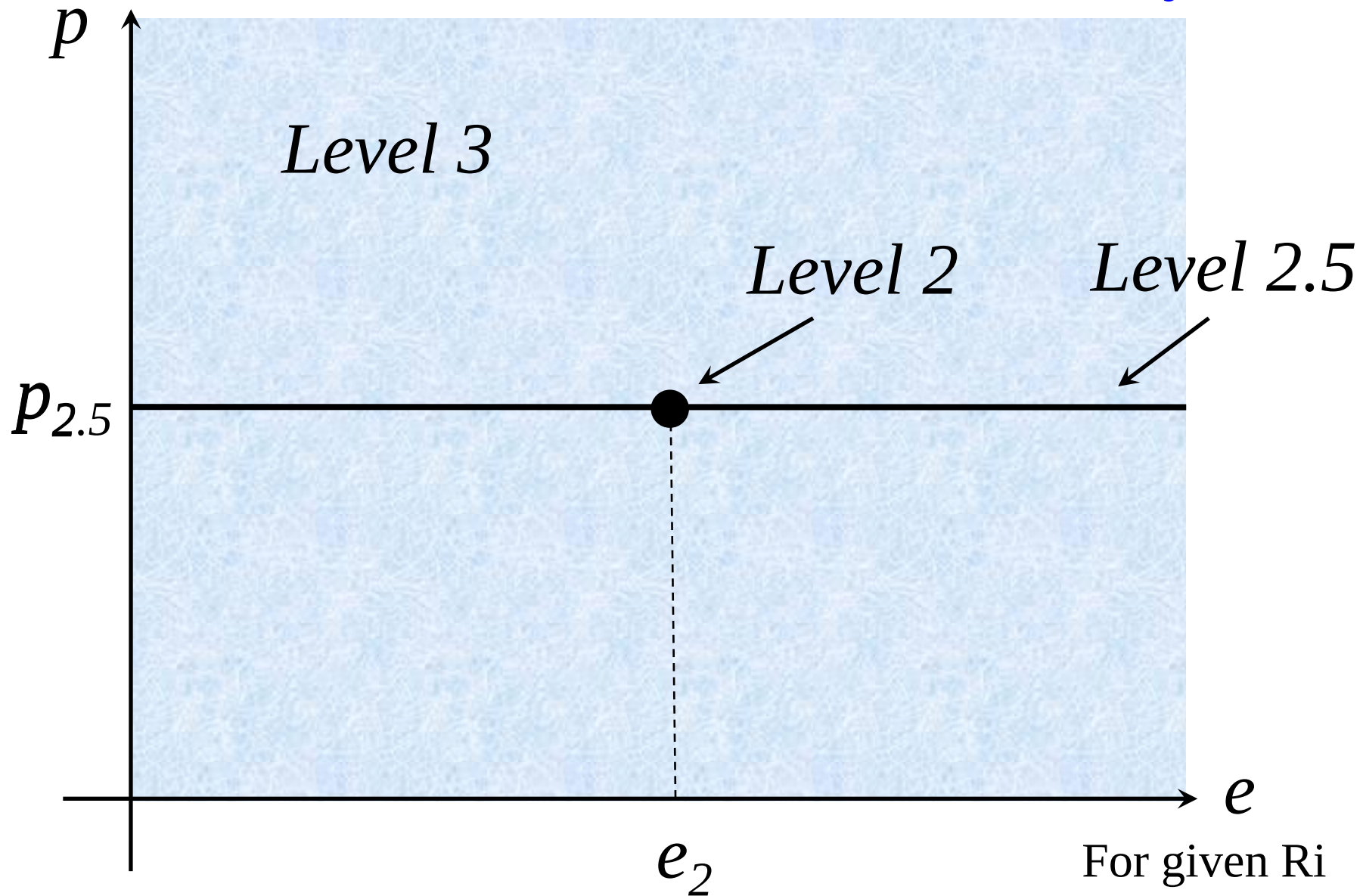
$\langle \theta_l'^2 \rangle$, $\langle q_t'^2 \rangle$, $\langle q_t' \theta_l' \rangle$ – potential energy of SGS motions (TPE)

Convection/stable stratification: TKE $\leftrightarrow$ TPE conversion

No reason to prefer one form of energy over the other!

- Consistent treatment of counter-gradient fluxes (not possible within algebraic and one-equation TKE schemes)
- Improved treatment of energy and flux production by buoyancy
- Better account for turbulence anisotropy (pressure effects!)
- (Potentially) improved coupling to tiled surface-layer scheme and to cloud scheme

Algebraic, TKE, and TKESV Schemes within the Mellor-Yamada Hierarchy



Governing Equations (prognostic)

TKE and scalar (co) variances

$$\frac{1}{2} \frac{\partial \langle u_i'^2 \rangle}{\partial t} = - \left(\langle w' u' \rangle \frac{\partial \langle u \rangle}{\partial z} + \langle w' v' \rangle \frac{\partial \langle v \rangle}{\partial z} \right) + \beta \langle w' \theta_v' \rangle - \frac{\partial}{\partial z} \left(\frac{1}{2} \langle w' u_i'^2 \rangle + \langle w' p' \rangle \right) - \varepsilon_e$$

$$\frac{\partial \langle \theta_l' q_t' \rangle}{\partial t} = - \langle w' q_t' \rangle \frac{\partial \langle \theta_l \rangle}{\partial z} - \langle w' \theta_l' \rangle \frac{\partial \langle q_t \rangle}{\partial z} - \frac{\partial \langle w' \theta_l' q_t' \rangle}{\partial z} - \varepsilon_{\theta q}$$

(non-stationarity)

(non-homogeneity)

Down-gradient diffusion formulation of the third-order transport

$$\frac{1}{2} \langle w' u_i'^2 \rangle + \langle w' p' \rangle = -C_e \tau_\varepsilon e \frac{\partial \langle u_i'^2 \rangle}{\partial z}, \quad \langle w' \theta_l' q_t' \rangle = -C_{sv} \tau_\varepsilon e \frac{\partial \langle \theta_l' q_t' \rangle}{\partial z}$$

Relaxation formulation of the dissipation rates

$$\varepsilon_e = \frac{\langle u_i'^2 \rangle}{\tau_\varepsilon}, \quad \varepsilon_{\theta q} = \frac{\langle \theta_l' q_t' \rangle}{R_\tau \tau_\varepsilon}, \quad R_\tau = \frac{\tau_{\theta q}}{\tau_\varepsilon}$$

Governing Equations (diagnostic)

Reynolds-stress and scalar-flux equations are reduced to algebraic relations by neglecting the third-order transport (diffusion) and the time-rate-of-changes terms. Once **pressure-scrambling terms** are parameterized, we obtain:

Momentum flux is **down-gradient**

$$\langle w'u' \rangle = -F_M \left(\tau_\varepsilon^2 S^2, Ri, \frac{P}{e} \right) \tau_\varepsilon e \frac{\partial \langle u \rangle}{\partial z}, \text{ similarly for } \langle w'v' \rangle$$

Scalar fluxes contain **non-gradient** terms (**that arise naturally from the governing equations rather than being introduced arbitrarily**)

$$\langle w'q_t' \rangle = -F_{H1}(\tau_\varepsilon^2 S^2, Ri, P/e) \tau_\varepsilon e \frac{\partial \langle q_t \rangle}{\partial z} + F_{H2}(\tau_\varepsilon^2 S^2, Ri) \tau_\varepsilon g \alpha \langle q_t' \theta_v' \rangle, \\ \text{similarly for } \langle w'\theta_l' \rangle$$

F_M , F_{H1} and F_{H2} are the so-called **stability functions** (Mellor and Yamada 1974) that **reflect parameterizations of the pressure-scrambling terms** (arguably the most important issue in second-order turbulence modelling).

Time and Length Scales

The various dissipation and return-to-isotropy time scales are set proportional to the TKE dissipation time scale

$$\tau_{\theta\theta} \propto \tau_{qq} \propto \tau_{q\theta} \propto \tau_{r\theta} \propto \tau_{rq} \propto \tau_{ru} \propto \tau_{\varepsilon}$$

TKE dissipation time scale in terms of length scale

$$\tau_{\varepsilon} = \frac{1}{C_{\varepsilon}} \frac{l}{e^{1/2}}$$

Blackadar-type formulation with buoyancy correction (baseline option)

$$\frac{1}{l} = \frac{1}{l_{\infty}} + \frac{1}{\kappa Z} + H(N^2) \frac{N}{C_N e^{1/2}}$$

Non-local formulation (e.g., Bougeault and André 1986, Bougeault and Lacarrère 1989): an advance option, (currently) more computationally expensive but is **often advantageous in terms of performance scores**

Effect of Clouds

Within turbulence schemes, it is not cloud cover per se but the effect of clouds on buoyancy production of TKE and scalar (co)variances that is a major concern.

Baseline option:

- **quasi-Gaussian scheme with exponential tail** (Bechtold et al. 1995) accounts, in an approximate way, for the effect of shallow cumuli [enhanced buoyancy production of TKE and scalar (co)variances and enhanced mixing in spite of small fraction cloudiness]

Available options:

- (i) **quasi-Gaussian scheme** (e.g., Sommeria and Deardorff 1977), a viable option but somewhat poor in terms of essential physical
- (ii) one more version of quasi-Gaussian scheme with exponential tail (Cuijpers and Bechtold 1995), insufficiently tested

Implementation into ICON

- **TKESV scheme is included into the official ICON code (August 2026)**
- Auxiliary features used operationally within the TKE scheme (Ri -dependent minimum diffusion coefficients, etc.) are available within TKESV
- Scientific documentation is available (Mironov and Machulskaya, 2017; Machulskaya and Mironov, 2018, 2020), technical documentation in preparation (Mironov et al. 2026)

New ICON modules: **mo_data_tkesv** and **mo_turb_tkesv**

Boundary Conditions

Surface

- Dirichlet b.c. for TKE (consistent with log-layer scaling, accounts for the limit of vanishing mean wind)
- Robin (aka impedance or convection b.c.) b.c. for scalar (co)variances (consistent with tile approach)
- Neumann b.c. for mean scalar quantities (temperature, humidity)
- Dirichlet (**recommended option**) or Neumann b.c. for mean wind. **Dirichlet b.c. increases numerical stability of the model but may violate momentum conservation. Neumann b.c. is likely a better option at small time steps.**

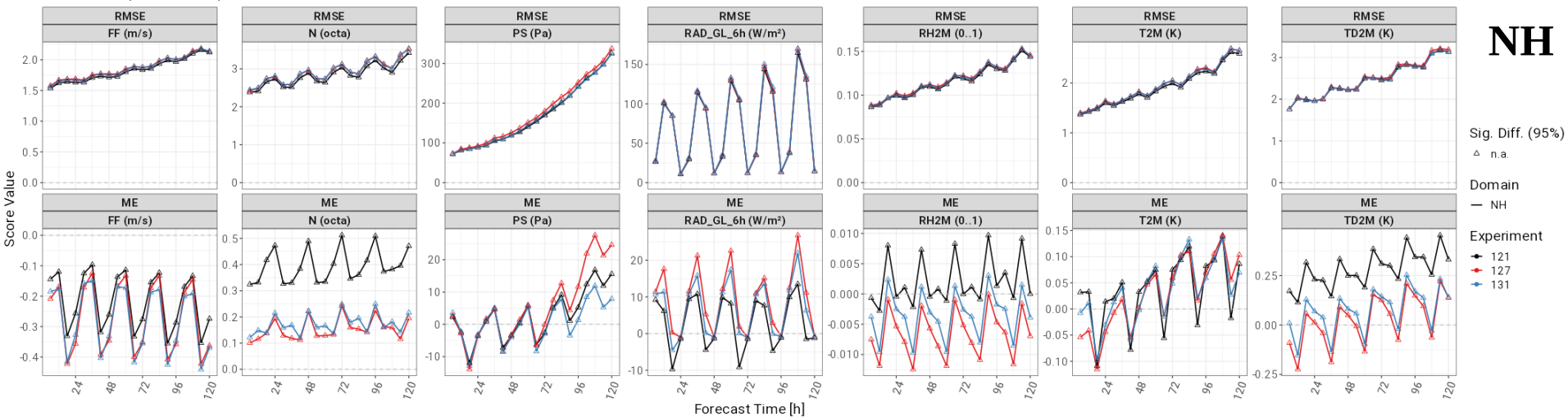
Top of the domain (level $kz=k_{st}$ that is specified by a user)

- Dirichlet b.c. for mean wind and mean scalars quantities (no turbulent mixing above the level k_{st})
- Dirichlet b.c. for TKE and scalar (co)variances (second-order moments are zero). **Robin b.c. is arguably a better option for second-order moments; not possible in global ICON due to a sponge near the domain top.**

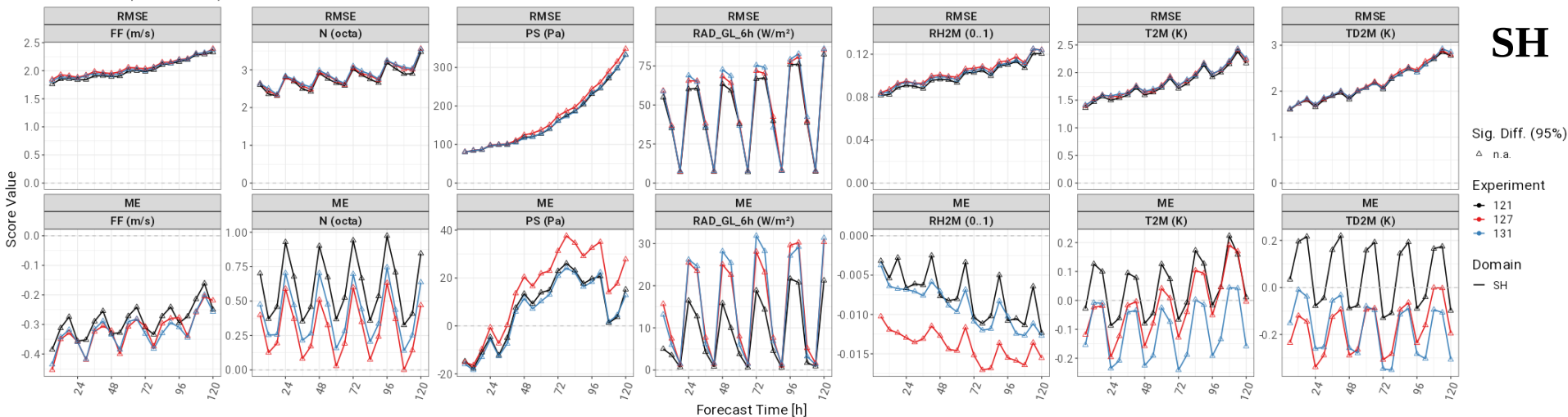
Results from Test Runs

ICON global R3B7 $\Delta t=120$ s, 01-31.05.2025, TKE vs. TKESV (BlackN+SFlight and NonLoc+SFull)

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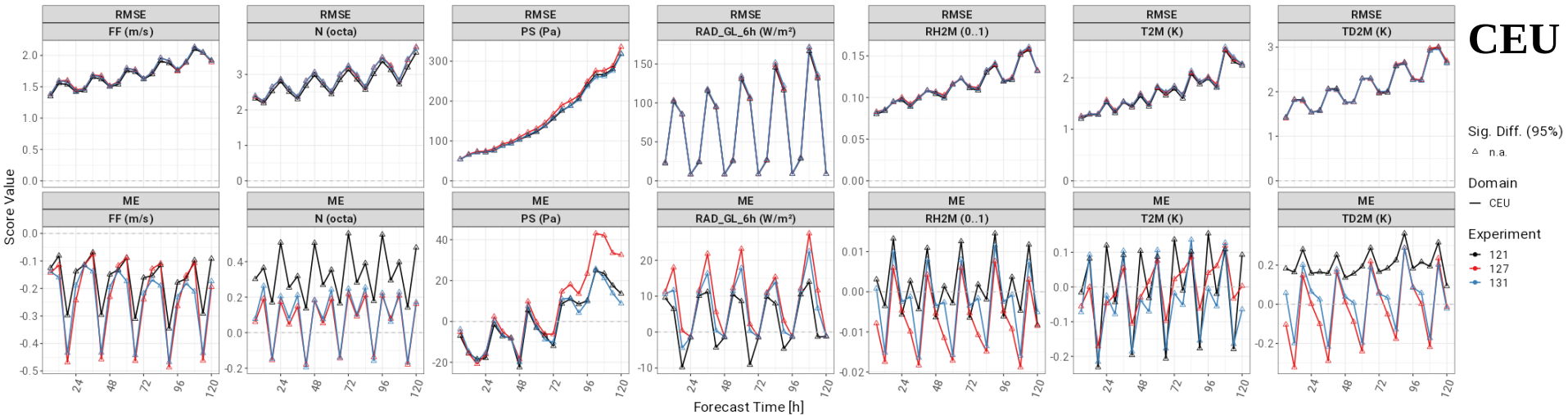
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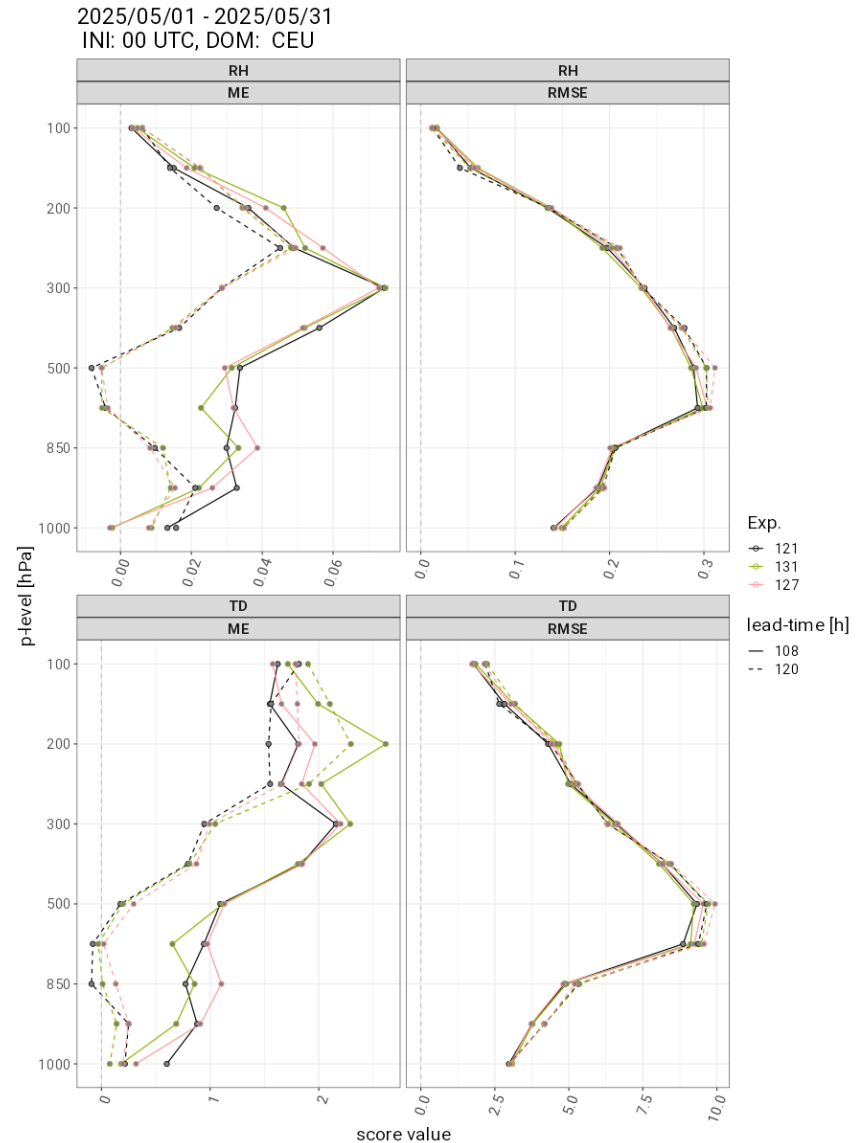
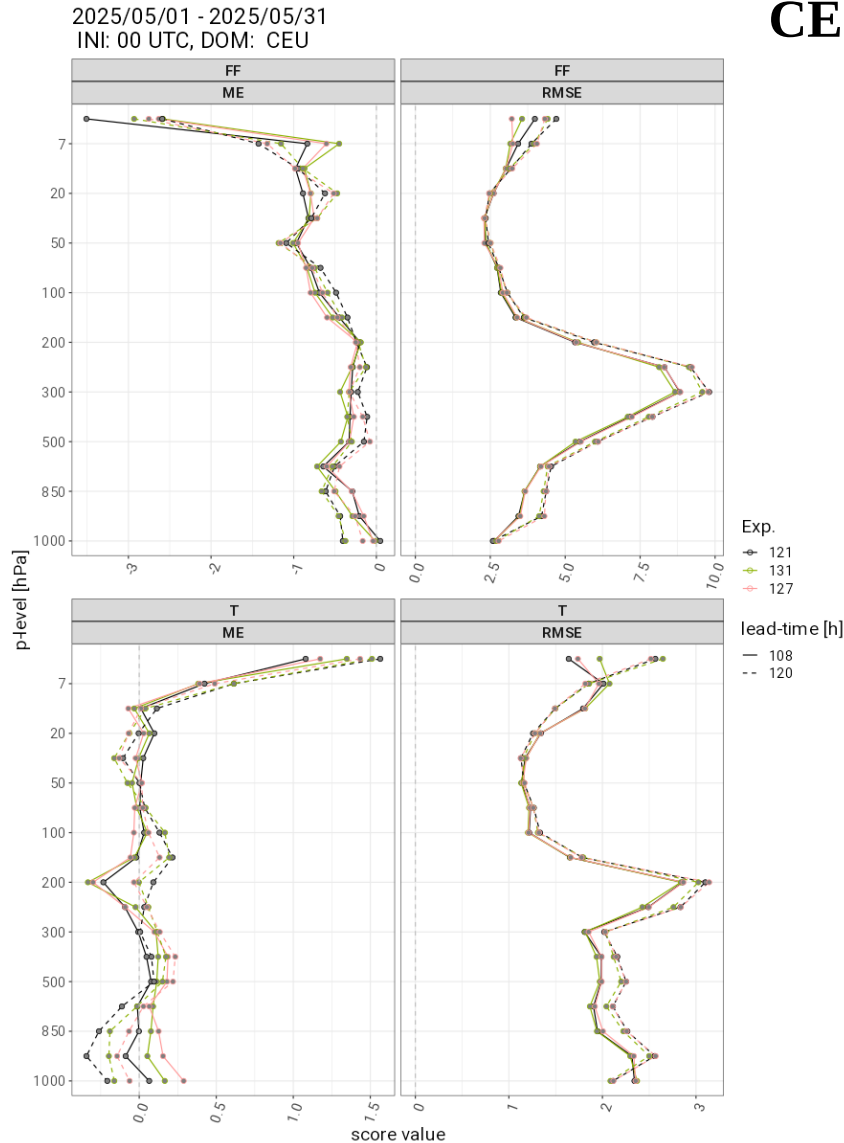
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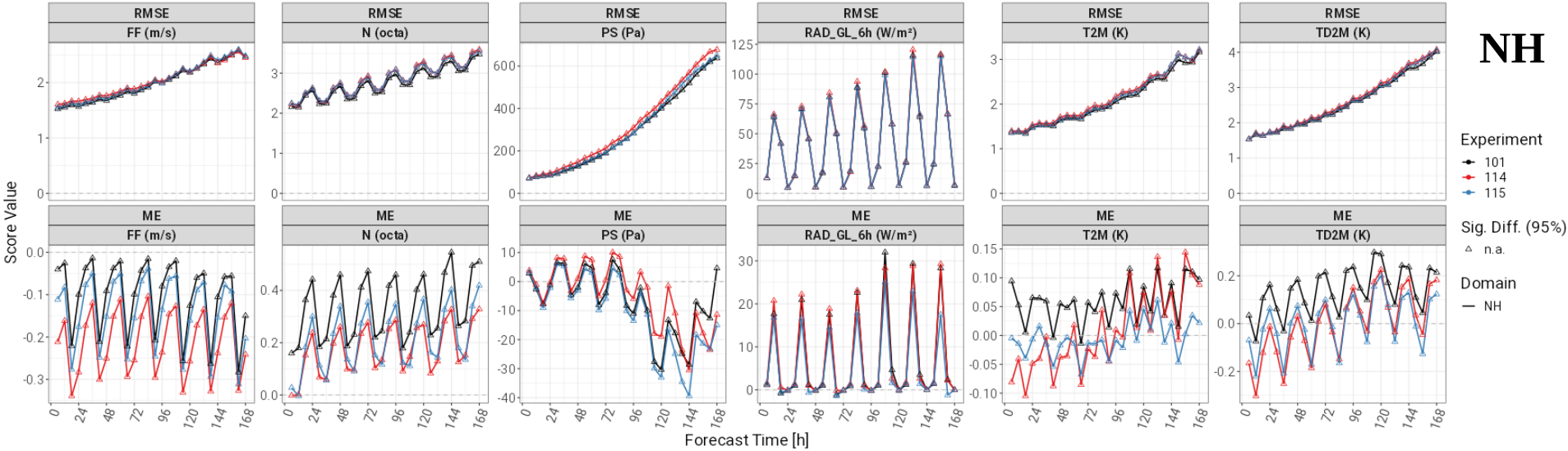


Results from Test Runs (cont'd)

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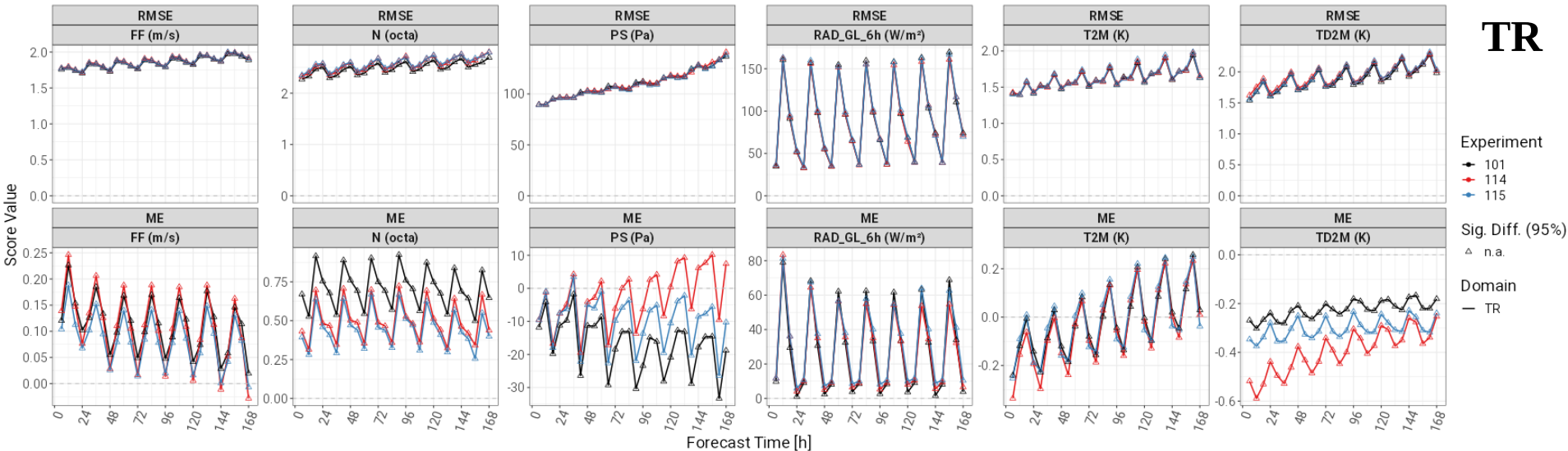
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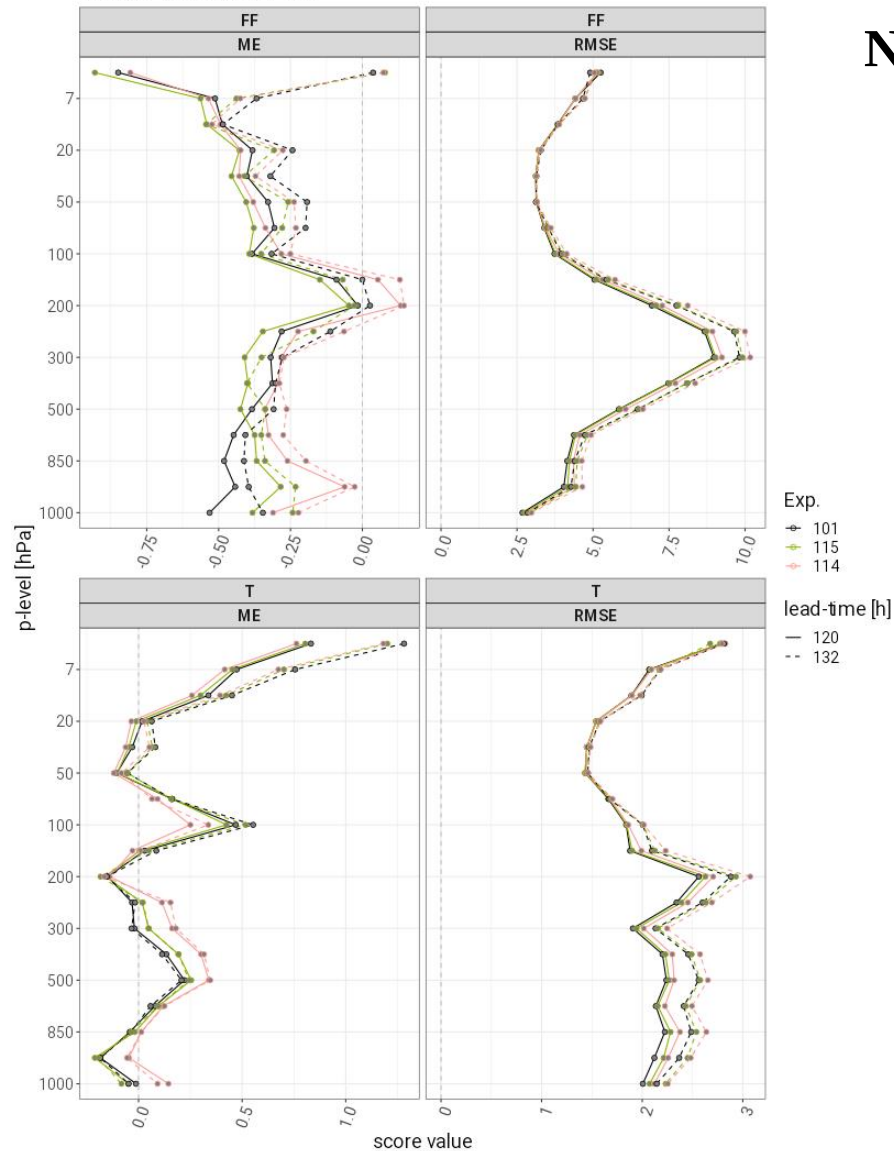
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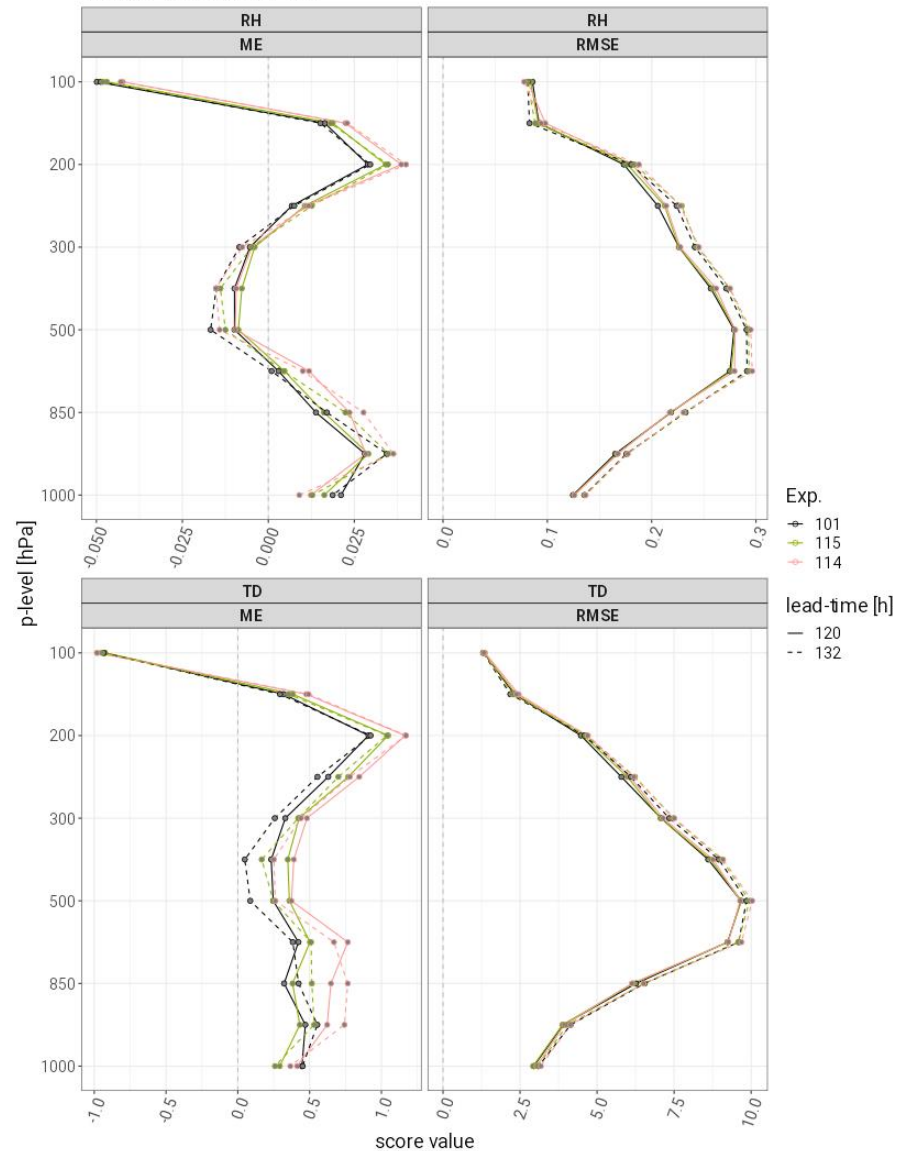
Results from Test Runs (cont'd)

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Scheme Configuration

MODULE `mo_data_tkesv` contains configuration switches and parameters

- *i_lengthtype* = *iBlackadarN* / *iNonLocal* (length scale)
- *i_sgscl* = *iBechtold* / *iGauss* (cloud scheme)
- *l_tkmintr*, *l_tkminstr*, *l_tkeshshr*, *l_tkessso* (auxiliary features used within the TKE scheme)
- *l_timesmth_var* (TKE and scalar (co) variances are smoothed in time, recommended for global runs)
- *l_sflight*, *l_inilight* (flux computation and initialization are based on slightly simplified stability functions)
- ... see **`mo_data_tkesv`** for further details
- See also a few hard-coded “tuning lines” in **`mo_data_tkesv`** (based on ICON global performance)

A Few Possibly Useful Hints

- Read the model documentation, at least skim through
- Look through the code (**mo_data_tkesv** and **mo_turb_tkesv**), it contains lots of comment lines
- Chose a configuration suitable for your application (docu may help; if it does not, ask the developers)
- *“All constants are tunable, but some constants are more tunable than others”*. If you change values of some constants or parameters of the TKESV scheme, make sure you understand what you are doing.
- **N.B.** The TKESV scheme may be somewhat demanding in terms of the time step and may have stability issues at large time steps (ICON global runs OK with 120s and 240s)

- Modification of parameterizations of the length scale and buoyancy terms
- Warm start for TKE and scalar (co)variances (arguably a better option for the DA cycle)
- Diffusion of passive scalars (e.g., coupling to ART) consistent with the TKESV physics (ad hoc solution available)

- **Length/time scale formulations** in the lower part of the boundary layer, optimization (some ideas available); and away from the surface (open issue, common for all turbulence schemes)
- Improved parameterizations of the **effect of clouds** on turbulence (likely skewness dependent)
- **Tuning** within full-fledged ICON (overall scores, etc.)
- **3D effects at high resolution** (horizontal scalar gradients and scalar-flux components, effects of SGS orography)

- Machulskaya, E., and D. Mironov, 2013: Implementation of TKE - Scalar Variance mixing scheme into COSMO. *COSMO Newsletter*, No. 13, 25-33.
- Mironov, D. V., and E. E. Machulskaya, 2017: A Turbulence Kinetic Energy – Scalar Variance Turbulence Parameterization Scheme. *COSMO Technical Report*, No. 30, 55 pp.
- Machulskaya, E., and D. Mironov, 2018: Boundary conditions for scalar (co)variances over heterogeneous surfaces. *Boundary-Layer Meteorol.*, **169**, 139-150. doi: 10.1007/s10546-018-0354-6
- Machulskaya, E., and D. V. Mironov, 2020: The stability functions and realizability of the Turbulent Kinetic Energy-Scalar Variance closure for moist atmospheric boundary-layer turbulence. *Boundary-Layer Meteorol.*, **176**, 197-228. doi: 10.1007/s10546-020-00528-7
- Mironov, D., E. Machulskaya, and R. Wirth, 2026: Turbulence Kinetic Energy – Scalar Variance turbulence parameterization scheme. Implementation into ICON and some useful hints. (In preparation)

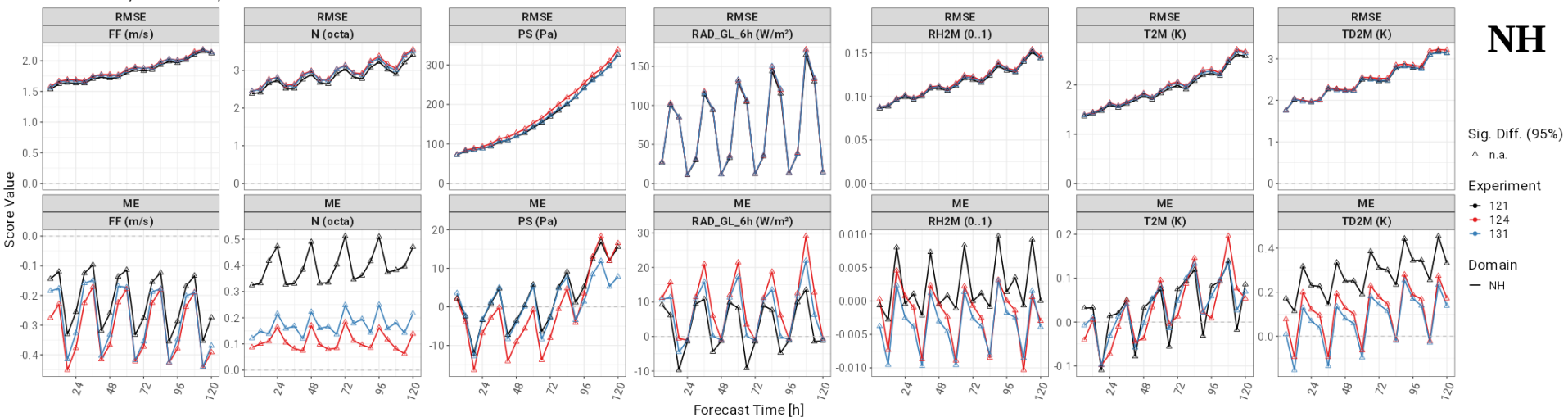
Thank you for your attention!

Acknowledgements: Jochen Förstner, Thomas Hanisch, Daniel Krüger, Vincent Larson, Marco Percivalle, Matthias Raschendorfer, Daniel Reinert, Daniel Rieger, Axel Seifert, Roland Wirth, Günther Zängl

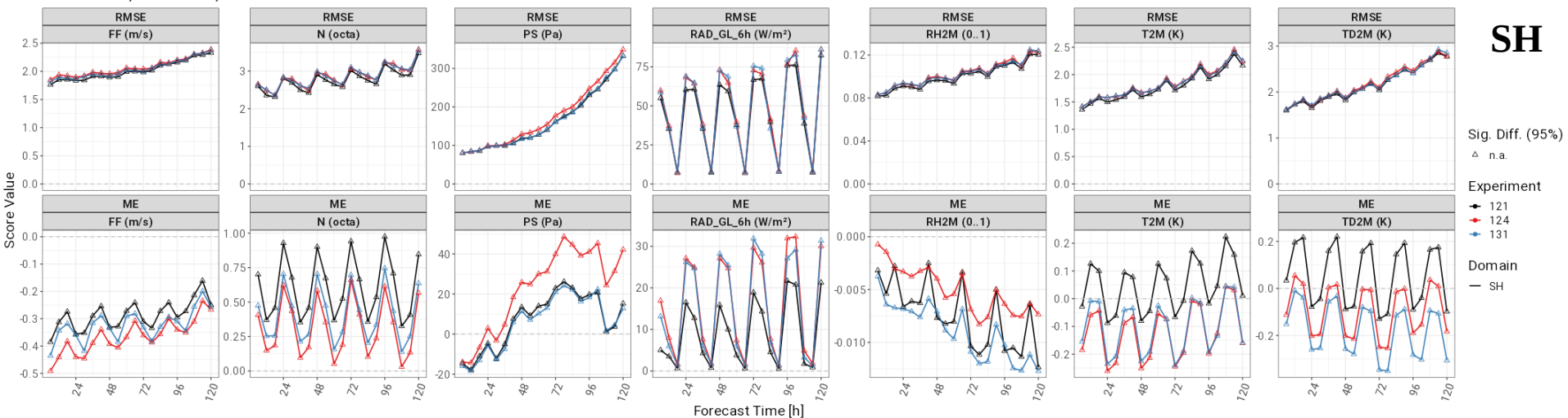
Results from Test Runs (cont'd)

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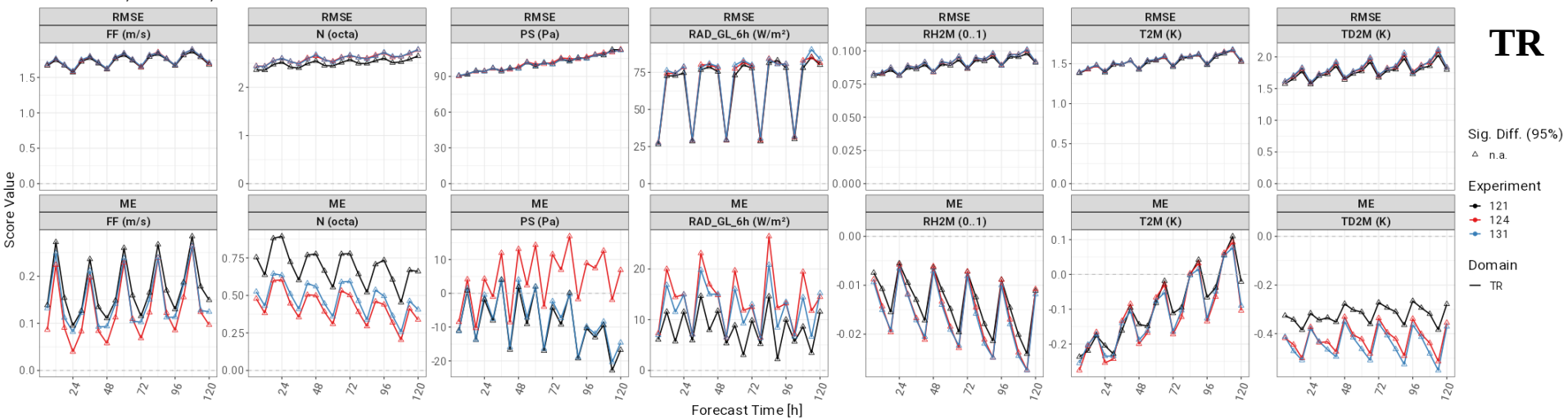
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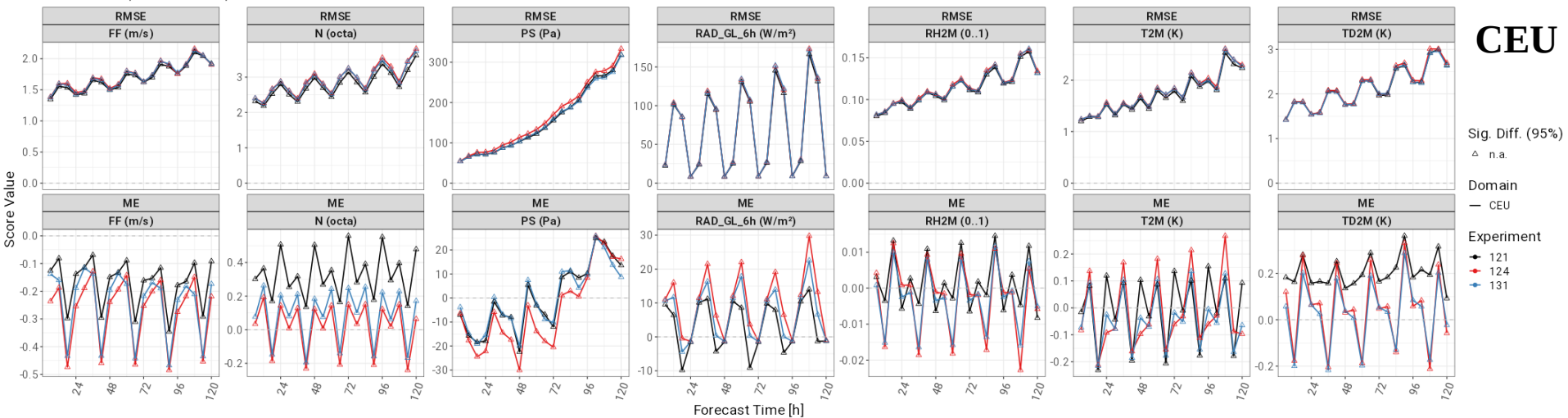
Results from Test Runs (cont'd)

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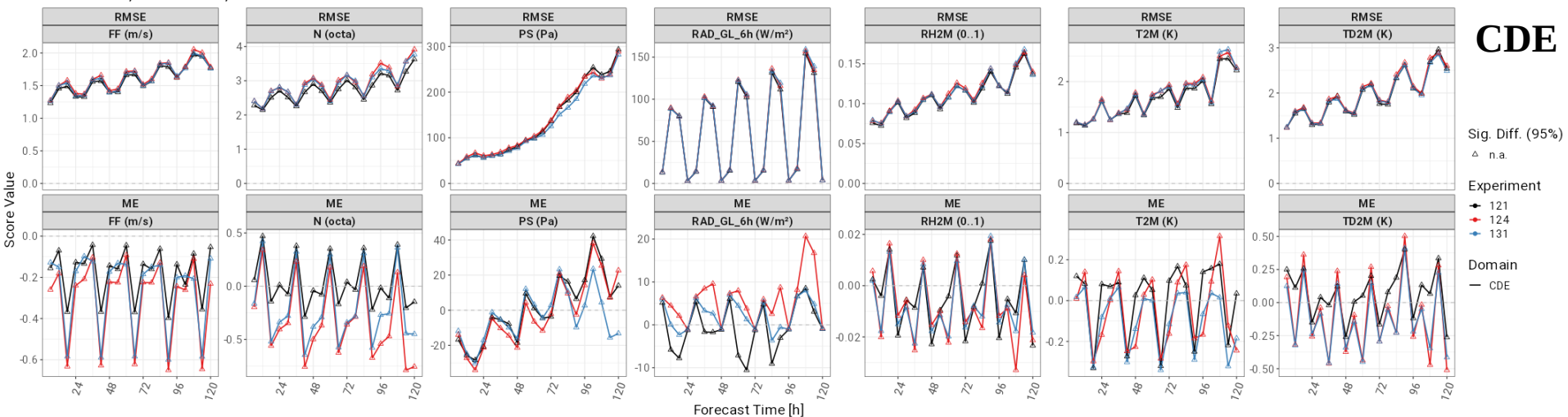


Results from Test Runs (cont'd)

ICON global R3B7 $\Delta t=120$ s, 01-31.05.2025, **SF light** vs. **SF full**

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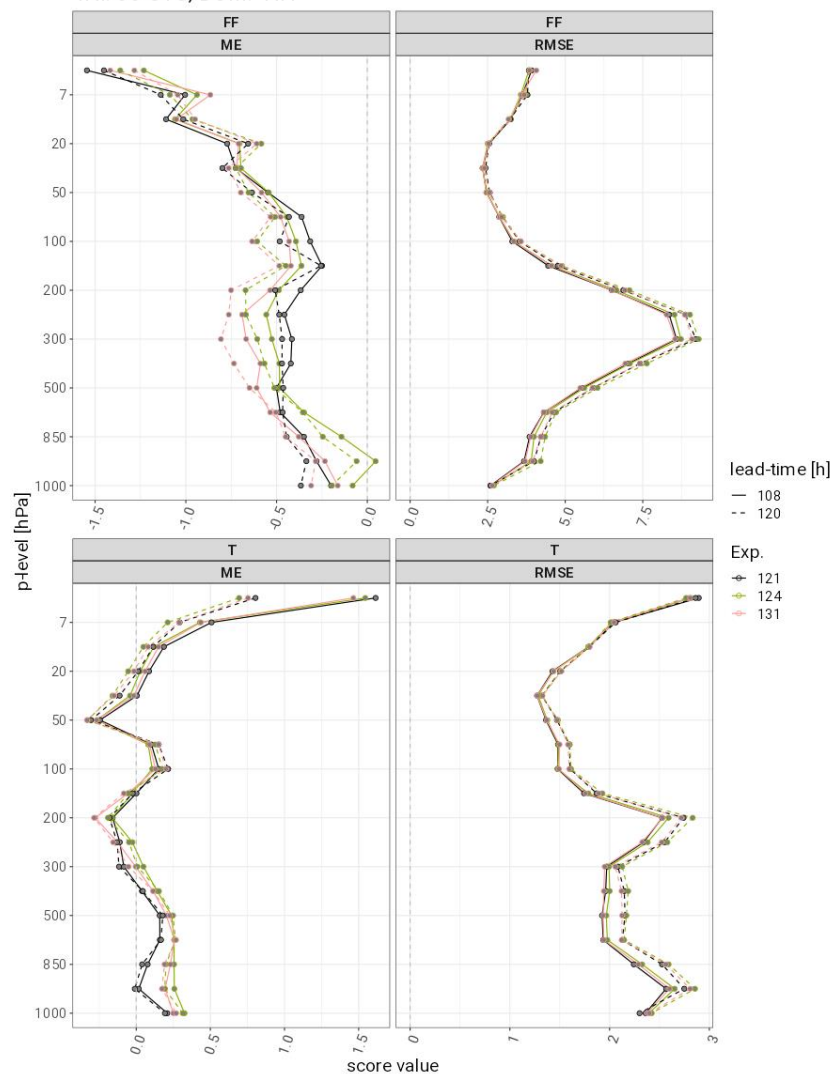


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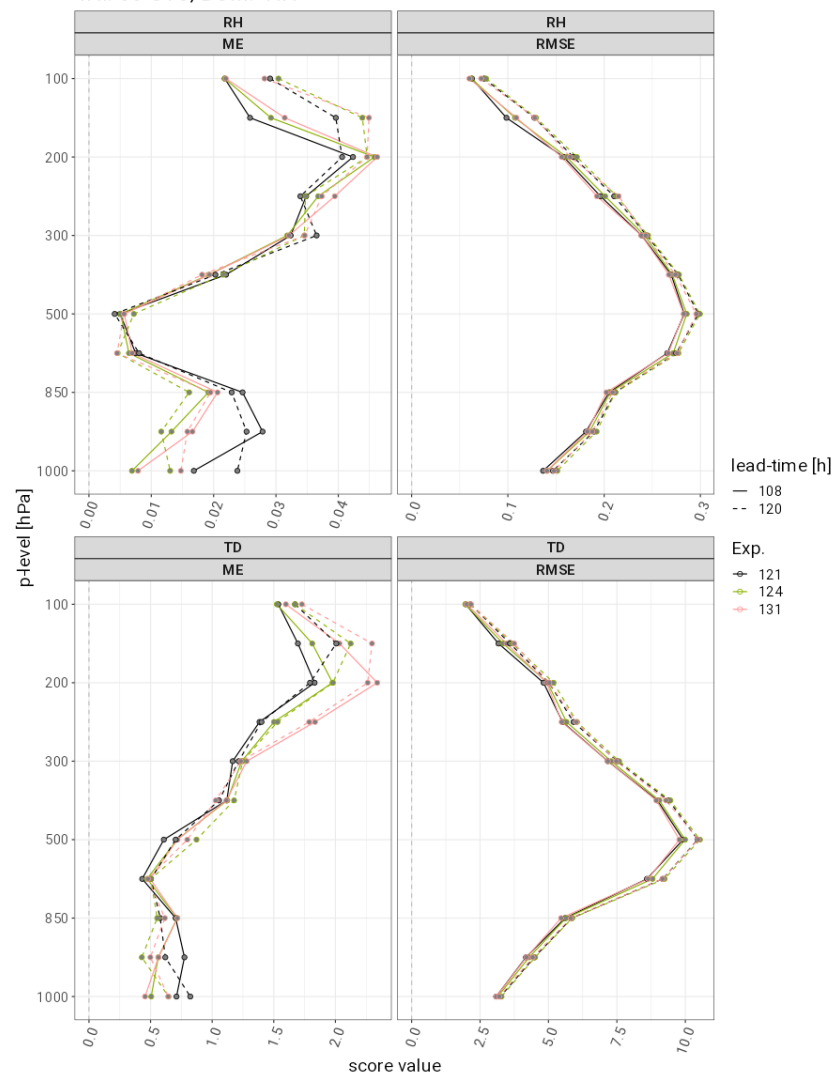
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NH

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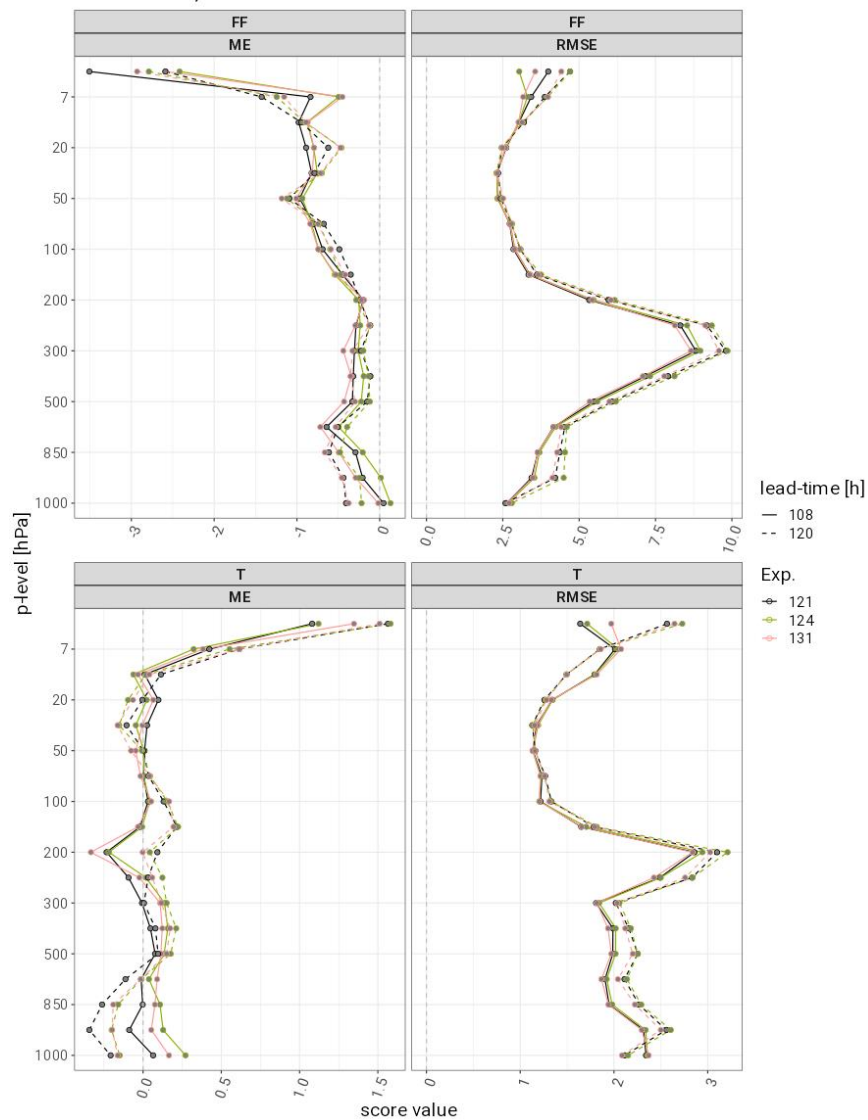
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CEU

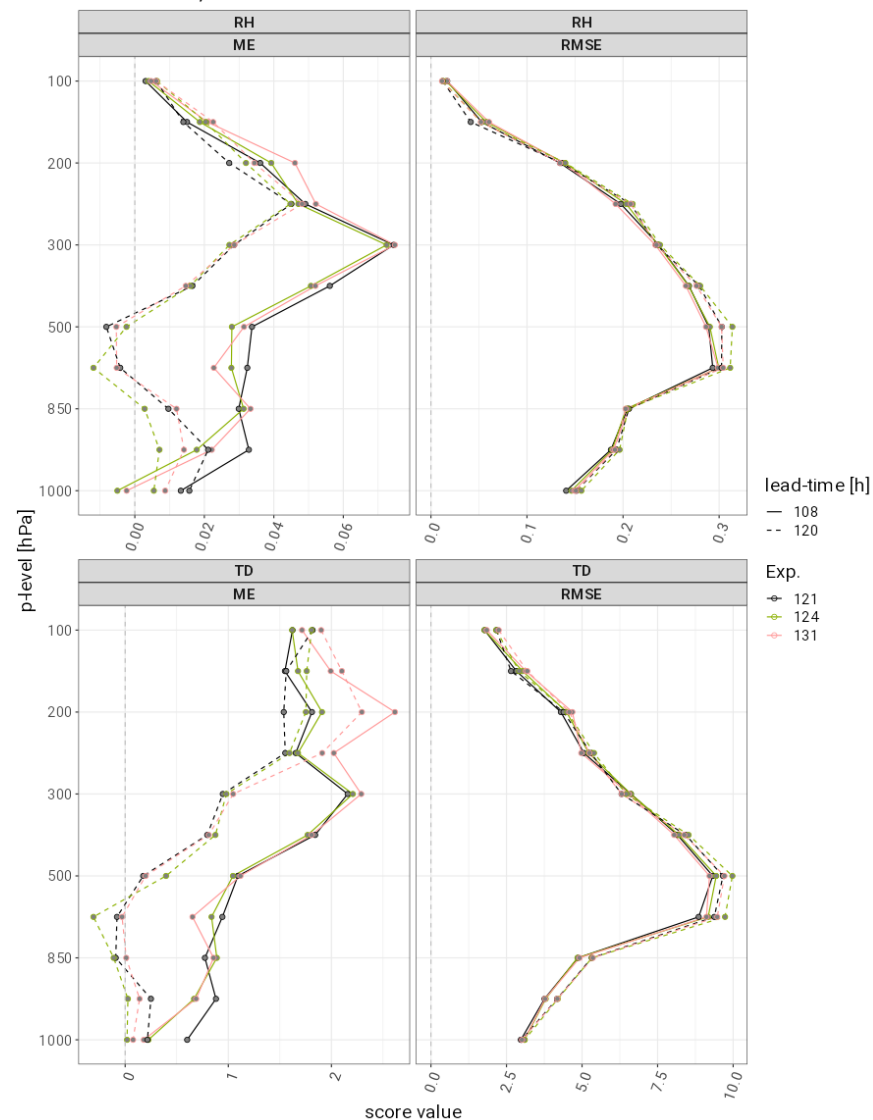
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Scheme Configuration

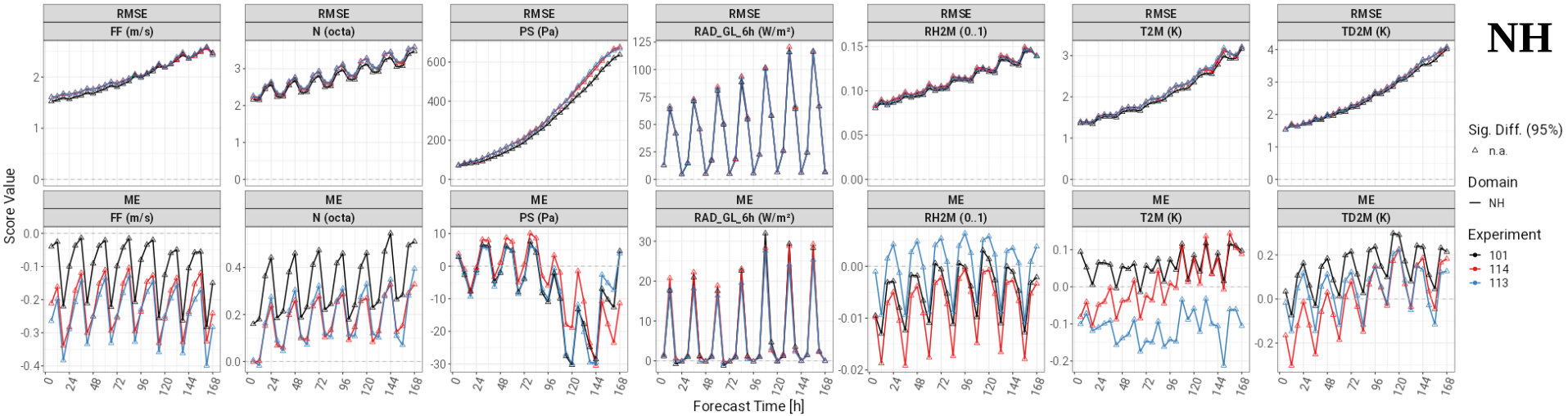
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- *l_tkmintr*, *l_tkminstr*, *l_tkeshshr*, *l_tkessso* (auxiliary features used within the TKE scheme)
- *l_qtprog* (prognostic equation for quasi-conservative variable $q_t = q_v + q_c$, is used, otherwise separate equations for q_v and q_c)
- *l_timesmth_var* (TKE and scalar (co) variances are smoothed in time, recommended for global runs)
- *l_sflight*, *l_inilight* (flux computation and initialization are based on slightly simplified stability functions)
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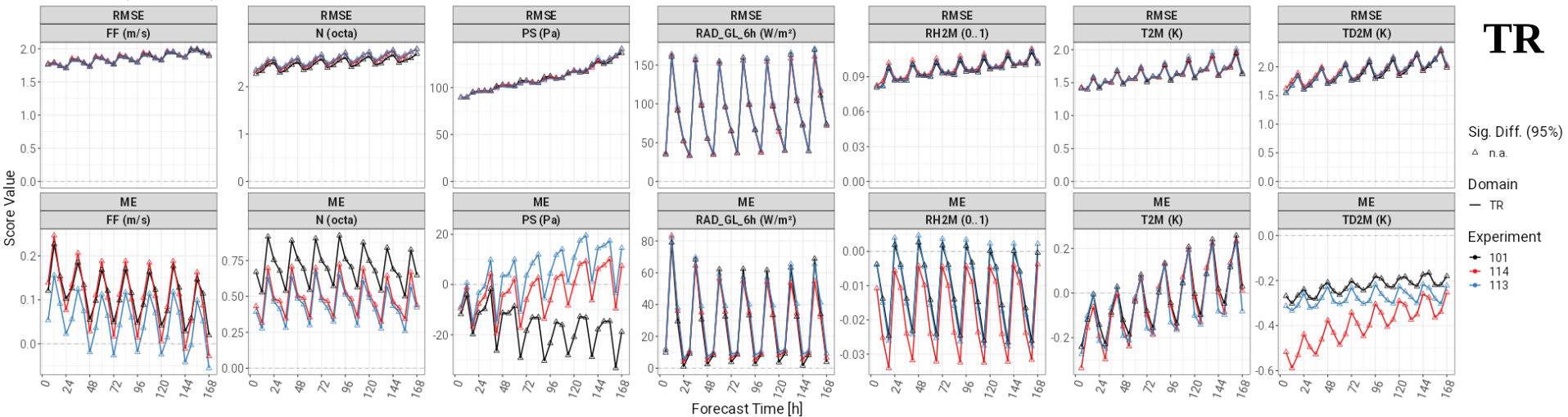
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