ICON

Recent work at DWD to improve model dynamics and physics in the stratosphere and mesosphere

ECMWF stratosphere workshop, 20.11.2019

Günther Zängl

Overview

- Introduction: the ICON modelling system and its configuration for operational NWP at DWD
- NWP-related work to reduce model biases in the lower / lowermost stratosphere
- Extension of the dynamical core and the physics parameterizations for upper-atmosphere applications
- Summary

Grid structure and operational configuration

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Icosahedral-triangular grid with two-way nesting capability

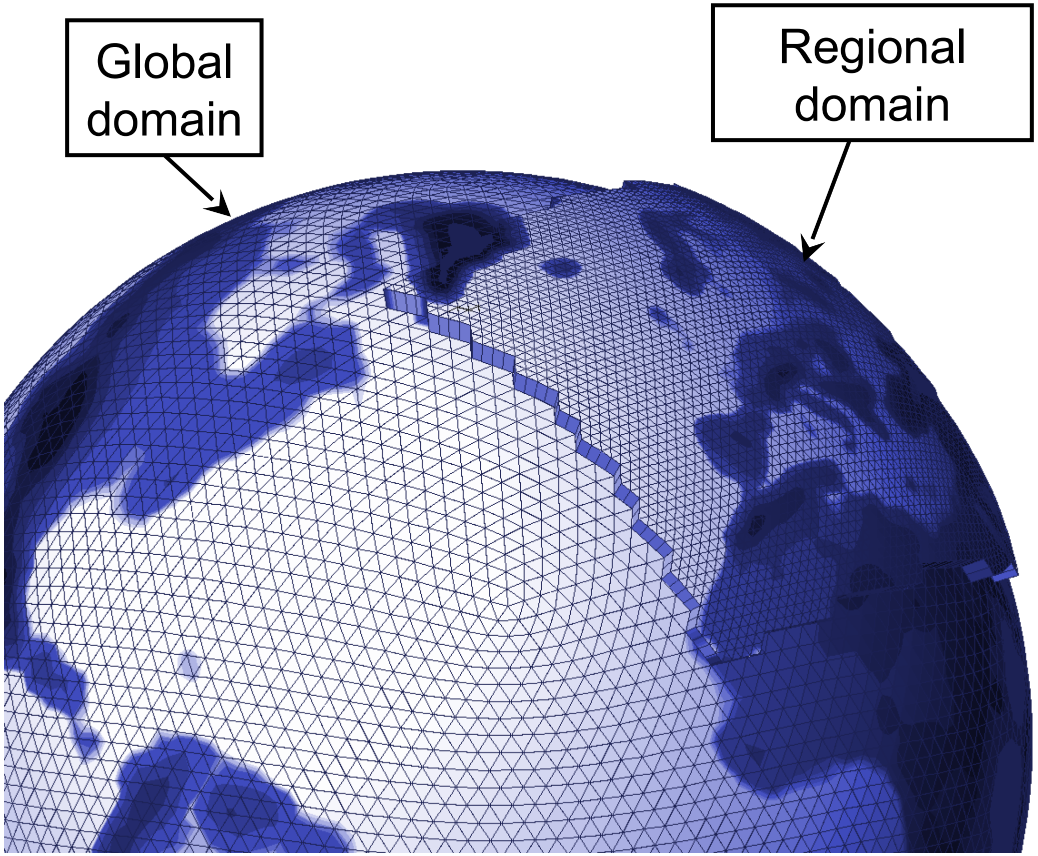
Grid generation starts with ‚root division' of the basic icosahedron by a choosable factor, followed by an arbitrary number of bisections

Operational configuration (since Jan 2015):

R3B7: root division n = 3, number of bisections k = 7

Mesh size: 13 km; 2.95 Mio grid points in global domain, 90 levels up to 75 km

The nested domain over Europe has a mesh size of 6.5 km (R3B8) and 60 levels up to 23 km



ICON: standard nonhydrostatic dynamical core

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- **Fully compressible nonhydrostatic vector invariant form, shallow atmosphere approximation**

$$\partial_t v_n + (\zeta + f)\, v_t + \partial_n K + w\, \partial_z v_n = -c_{pd}\theta_v \partial_n \pi$$

Edge normal velocity

$$\partial_t w + \vec{v}_h \cdot \nabla w + w\, \partial_z w = -c_{pd}\theta_v \partial_z \pi - g$$

Vertical velocity

$$\partial_t \rho + \nabla \cdot (\vec{v}\rho) = 0$$

Full air density

$$\partial_t(\rho\theta_v) + \nabla \cdot (\vec{v}\rho\theta_v) = 0$$

Virtual potential temperature

$(v_n,\ w,\ \rho,\ \theta_v\ :\ \text{prognostic variables})$

Additional prognostic variables for q_v, q_c, q_i, q_r, q_s and TKE)

Solver:

- **Finite volume/finite difference discretization (mostly 2nd order)**
- **Two-time level predictor-corrector time integration**
- **Vertically implicit (vertical sound-wave propagation)**
- **Fully explicit time integration in the horizontal (at sound wave time step; not split explicit!)**
- **Local mass conservation and tracer-mass consistency**

Zängl, G., D. Reinert, P. Ripodas, and M. Baldauf, 2015, QJRMS

NWP-related work to reduce model biases in the lower / lowermost stratosphere

- Bias issues related to the impact of ozone and moisture on radiative heating / cooling

- Bias issues related to (parameterized) gravity-wave forcing in the stratosphere

Ozone-tropopause coupling

- Motivation: cold bias above the tropopause, particularly in NH spring and summer
- Goal: adjust ozone concentration to the position of the TP and mimic the ozone jump occurring across the TP for sharp, anticyclonically influenced TPs (without incurring the additional complexity and computational cost for fully prognostic ozone)
- Method: diagnose thermal TP at each radiation time step, followed by a vertical shift of the ozone climatology (by at most 125 hPa) depending on the TP sharpness
- In the absence of a well-defined thermal TP, climatological ozone values are left unchanged
- Ozone-TP coupling is restricted to extratropics

Impact of ozone-TP coupling: Radiosonde verification for temperature, NH, June/July 2018

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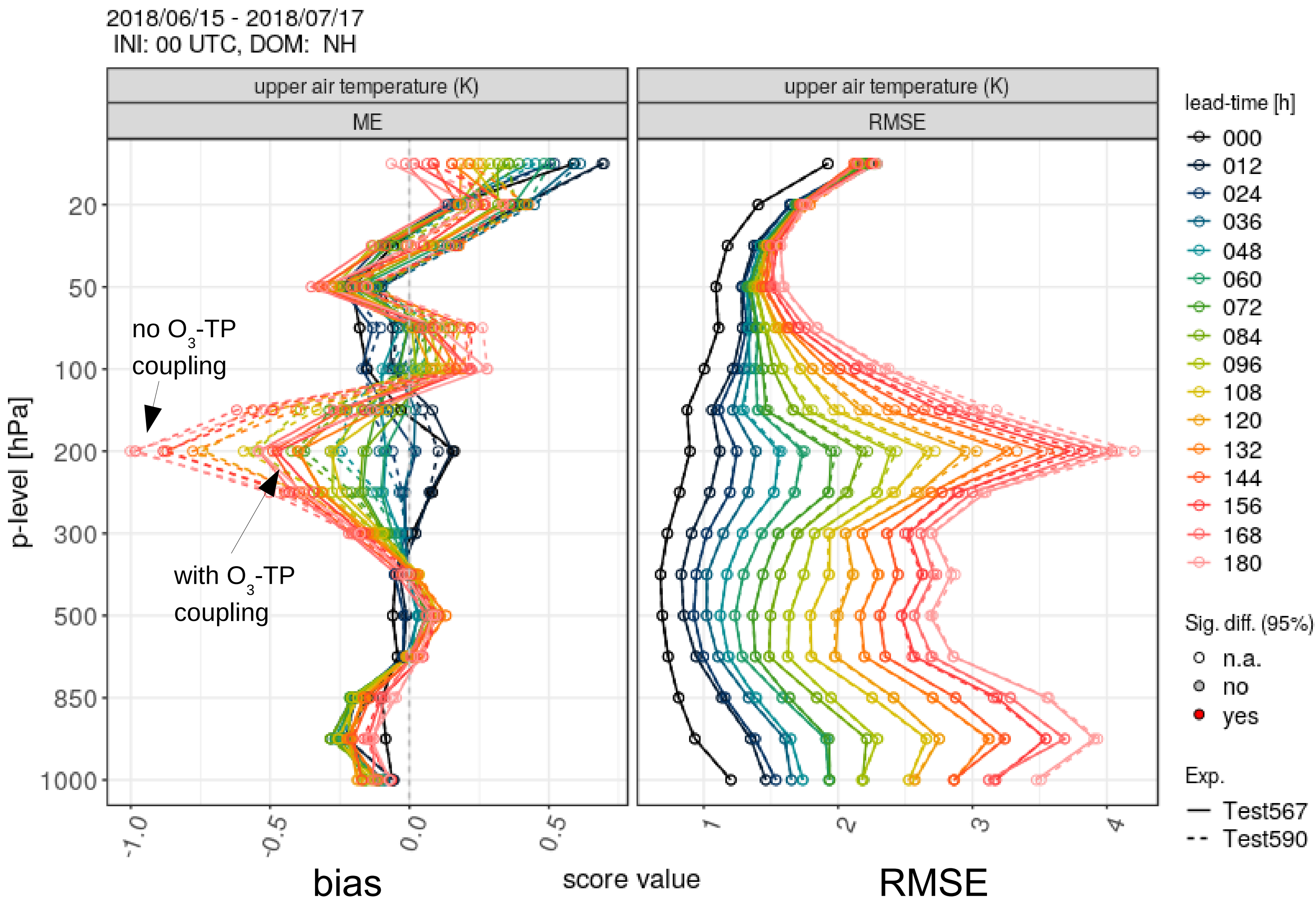

Corresponding scorecard (relative change of RMSE)

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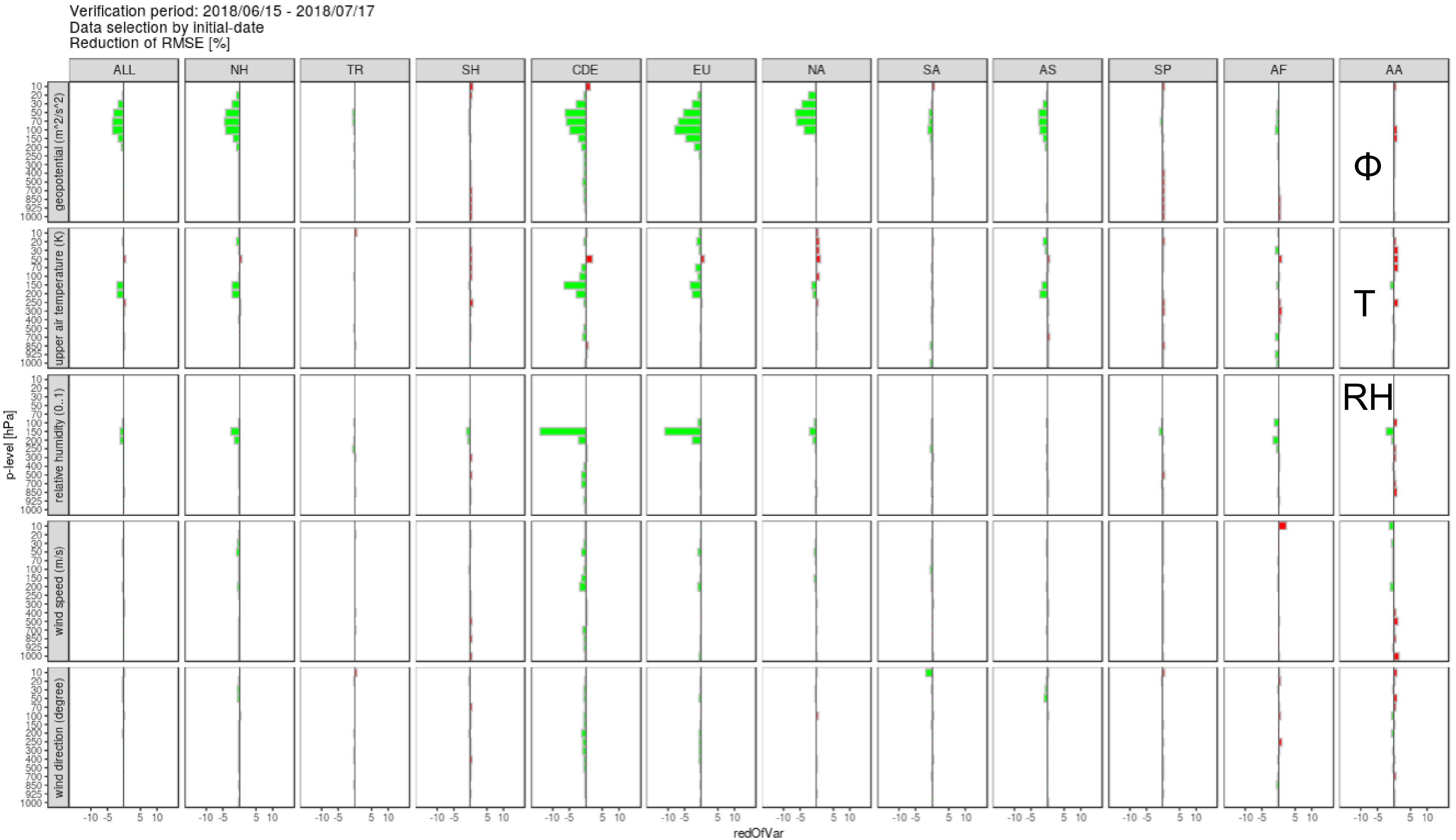

Ozone climatology and temperature biases

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- **ICON started in 2015 with the GEMS ozone climatology used in earlier times at ECMWF**
- **Subsequent verification indicated a marked annual cycle of the temperature bias in the lower tropical stratosphere and a large cold bias in the Antarctic stratosphere in spring (‚ozone hole season')**
- **Tests with the more recent MACC climatology showed improvements for both bias issues**
- **Unfortunately, MACC introduced degradations in other regions/seasons, so that we decided to use a ‚blending' between both climatologies for the time being**

Tropics, 50 hPa, May 2015 – Jan 2017

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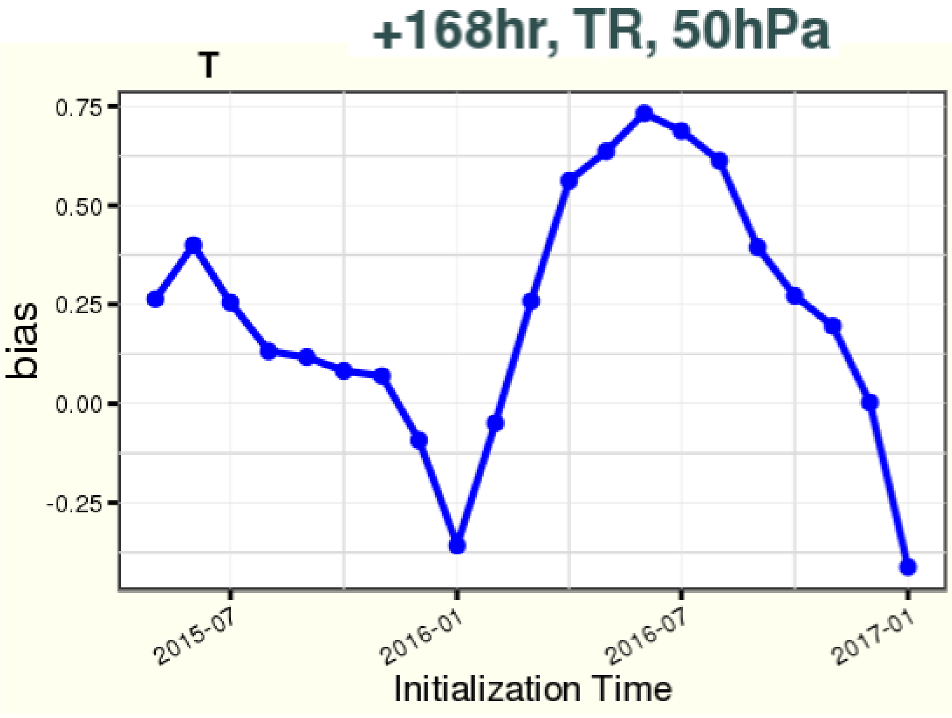
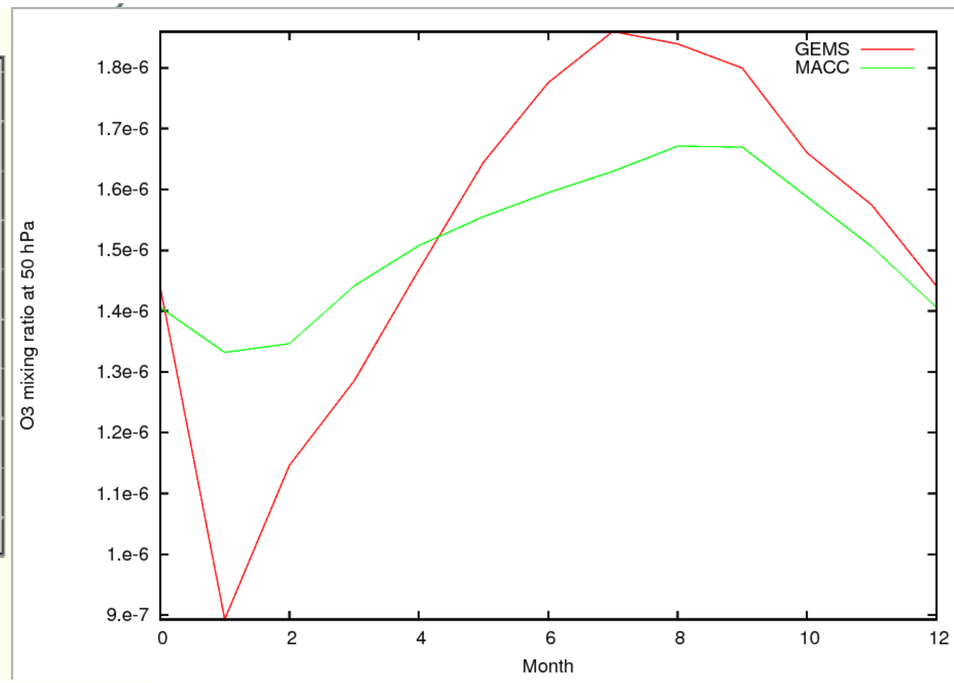
Left: temperature bias (tropics) against analyses on day 7
Right: Tropical ozone mixing ratios at 50 hPa according to GEMS and MACC





Better, but room for further improvement …

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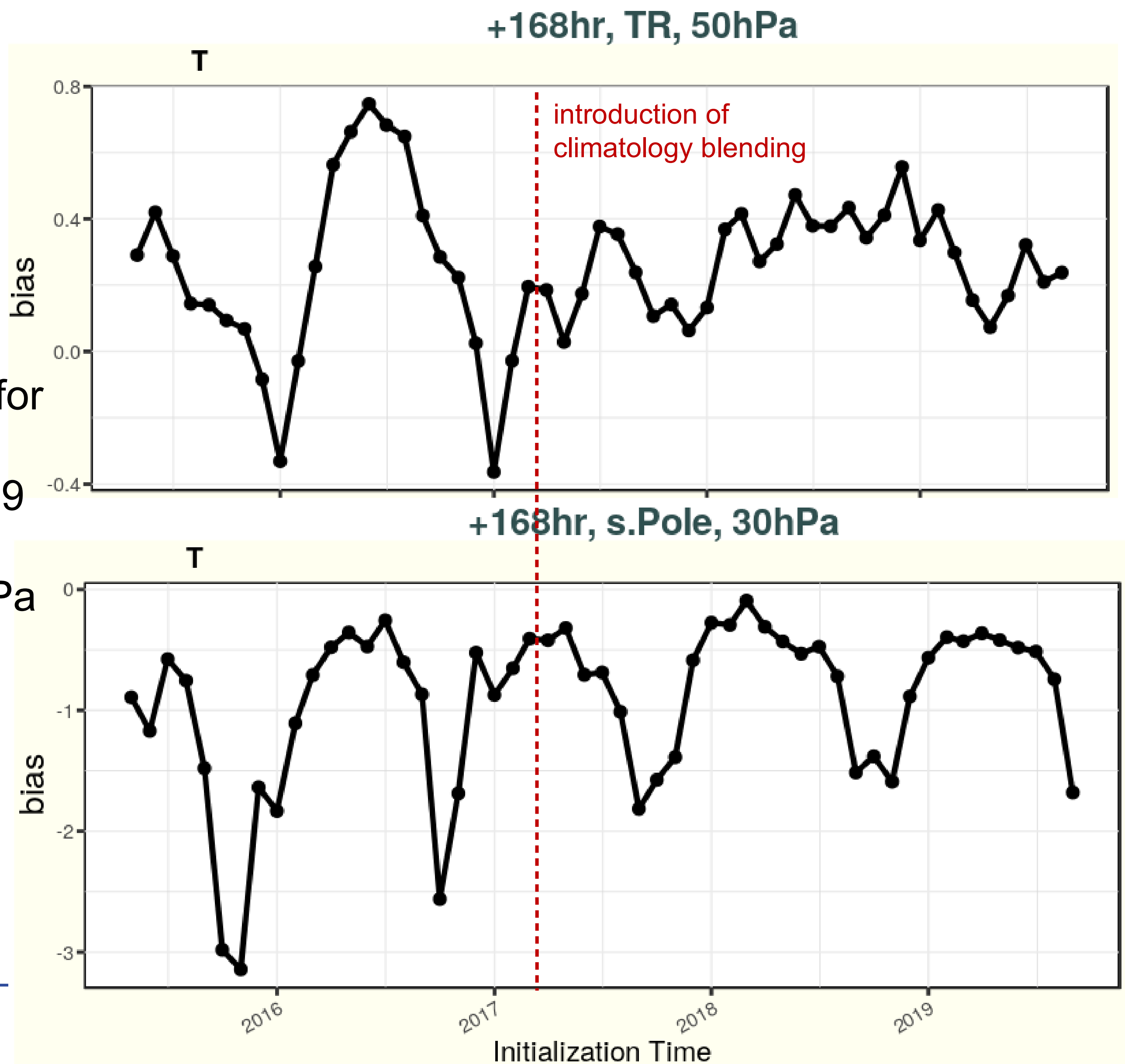
Analysis verification for day 7,
May 2015 – Sep 2019
top: Tropics, 50 hPa
bot: Antarctica, 30 hPa



Overshoot limiter in convection scheme

- Besides a cold bias, verification against radiosondes indicates too high moisture above the extratropical tropopause, which indirectly contributes to the cold bias by enhanced radiative cooling
- Initially, diffusivity of model numerics (moisture transport) was thought to be the main reason, but an improved implementation of the (vertical) flux limiter had only a minor impact
- Later on, the convection scheme was identified as an important source of the moist bias because overshooting convection is not (cannot be?) adequately represented
- An artificial limiter for overshooting in stable environments (stratosphere) brought a substantial improvement

- Also successfully tested in IFS

Overshooting convection

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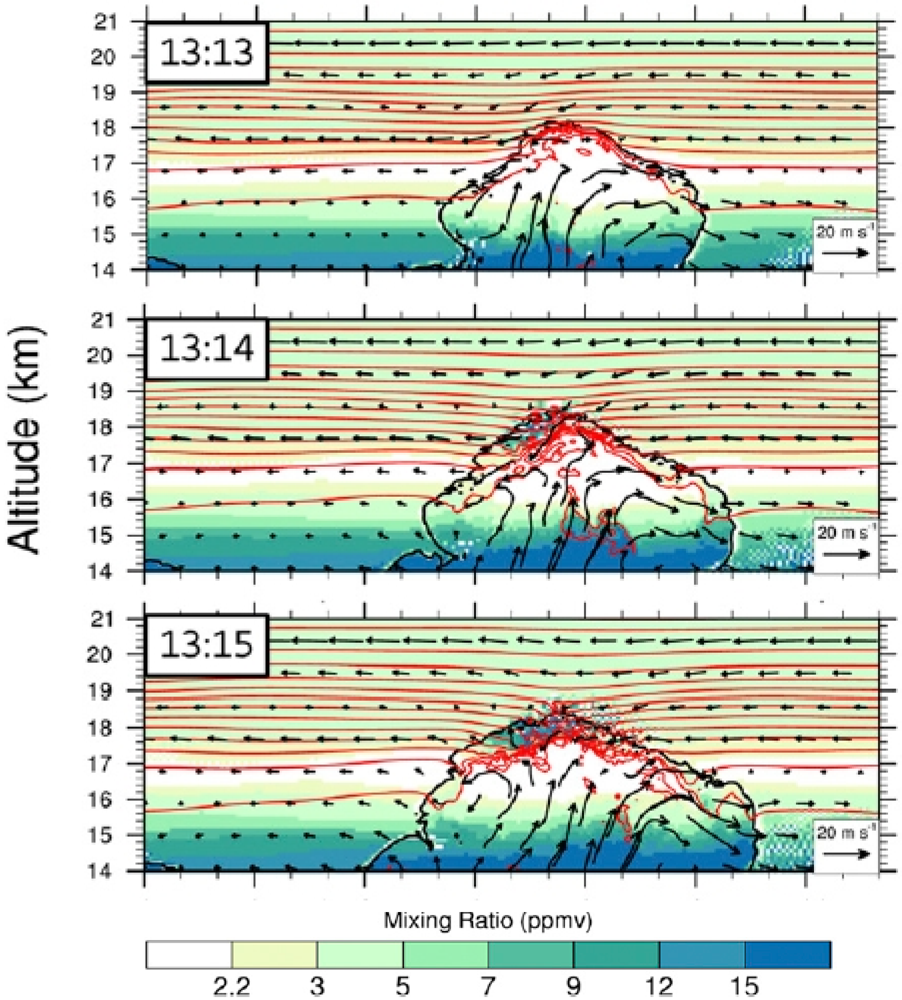
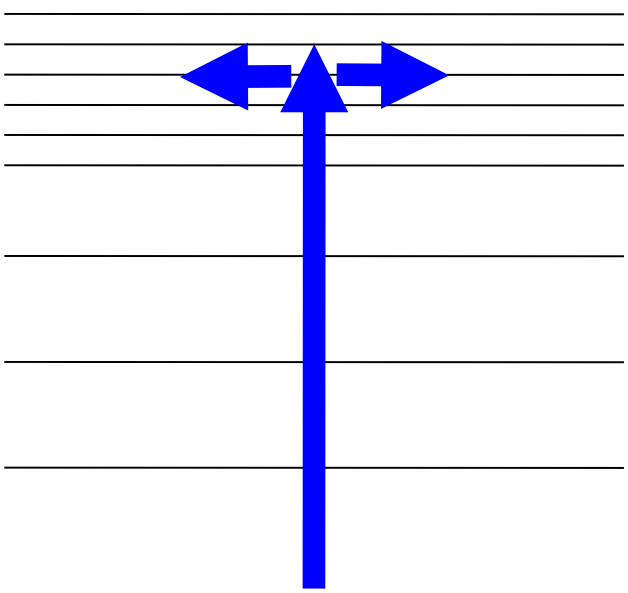


Nature as represented by LES
(Dauhut and Chaboureau 2018, JAS)



Overshoots in parameterized convection: moisture detrainment takes place too high above the tropopause

Radiosonde verification for rel. humidity, NH, April/May 2019

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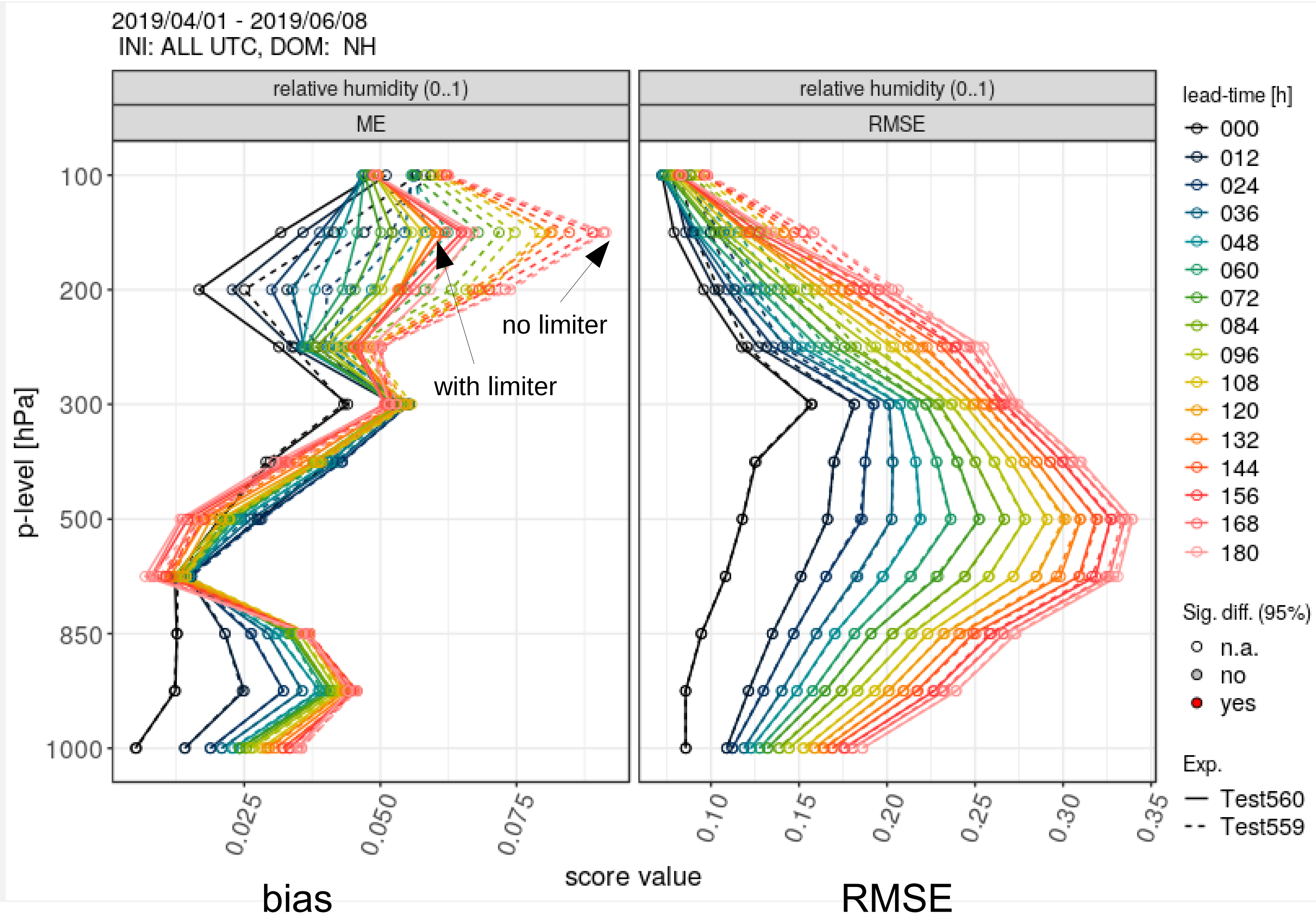
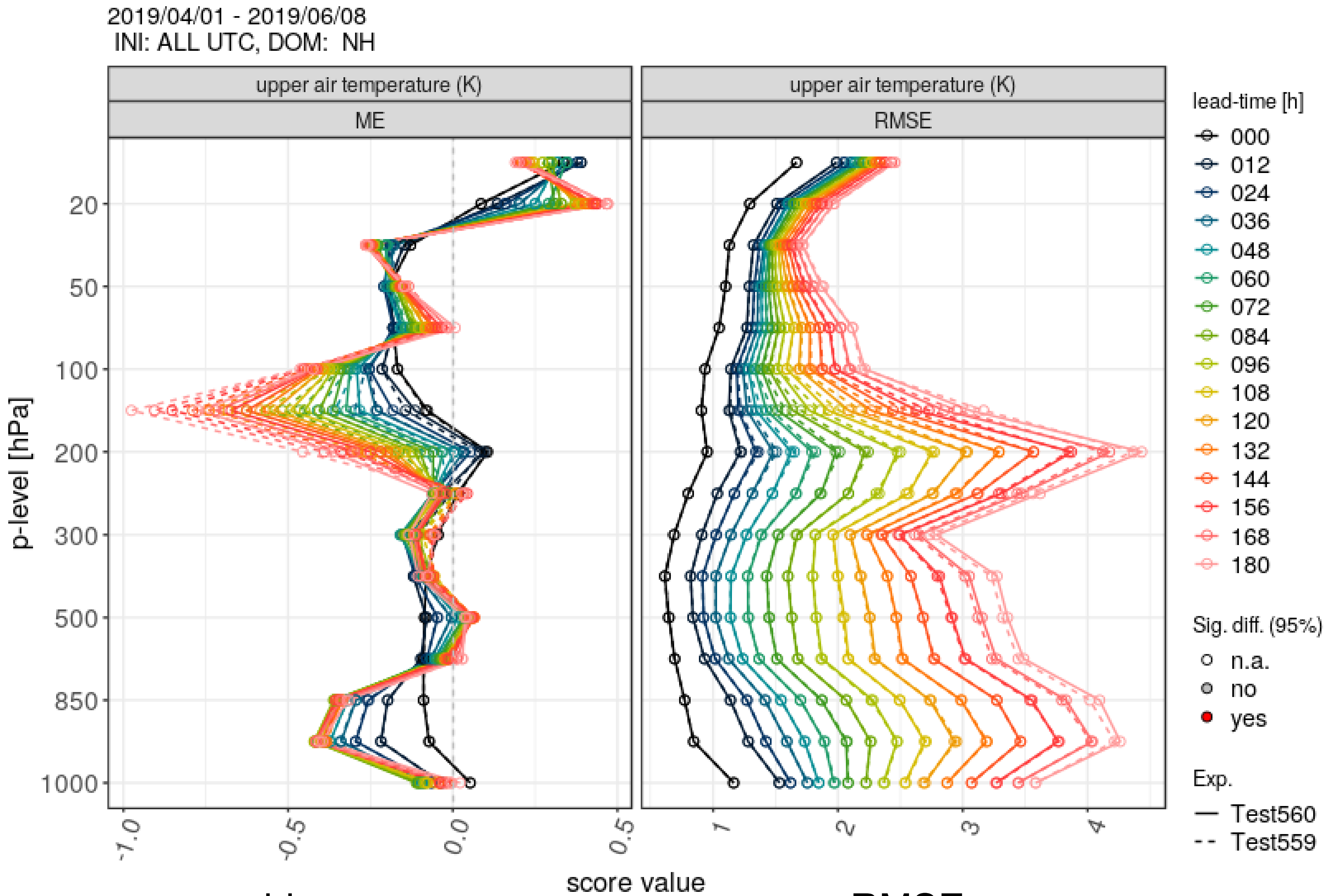


Radiosonde verification for temperature, NH, April/May 2019



bias

RMSE

Scorecard for recent parallel routine phase (mid-August – late October 2019)

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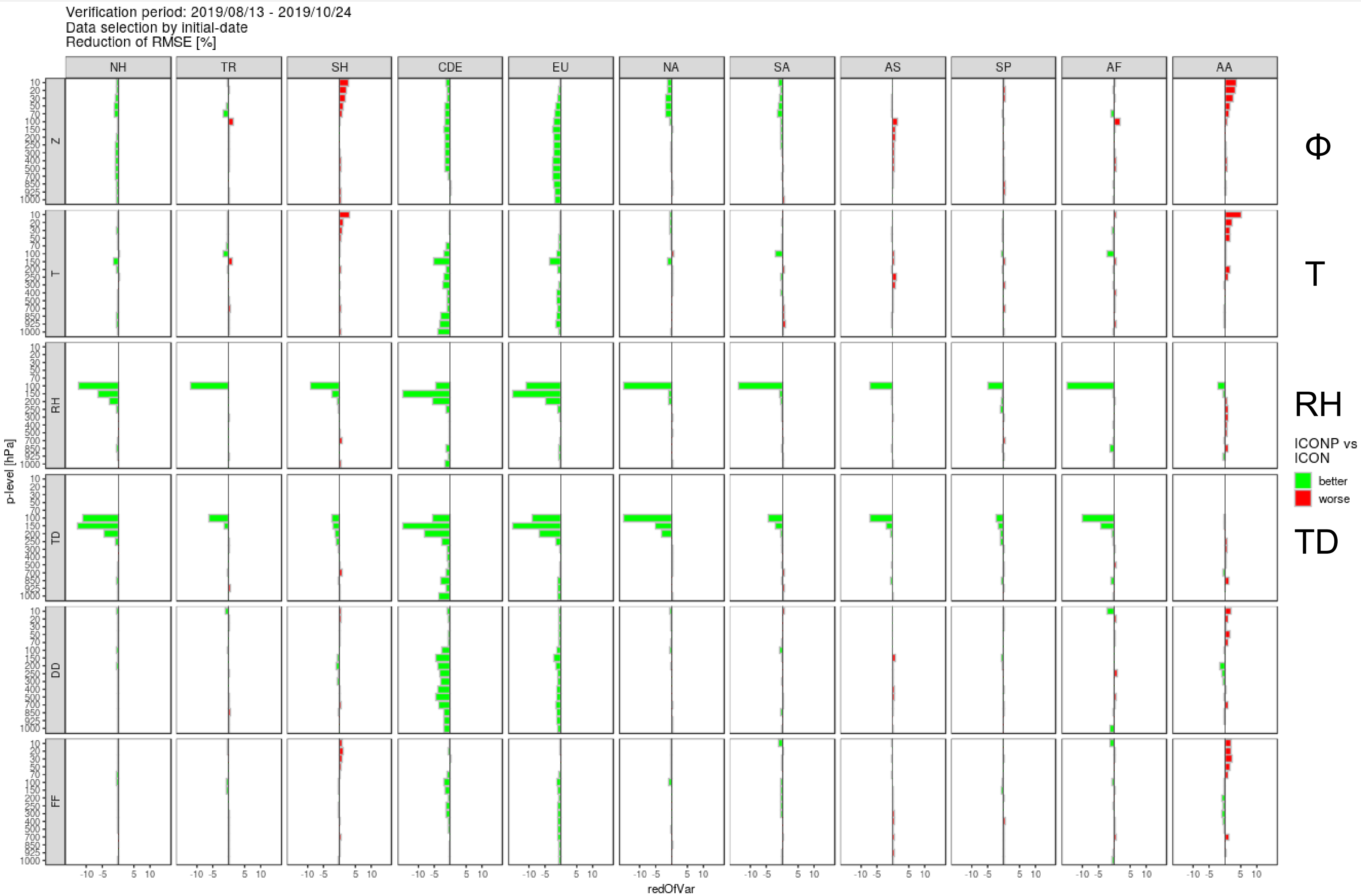

Issues related to parameterized gravity-wave forcing

- In the first two years of operational ICON forecasts, we noticed a large warm bias in the Arctic middle stratosphere peaking in early winter

Analysis verification for Arctic at 5 hPa, May 2015 – October 2016

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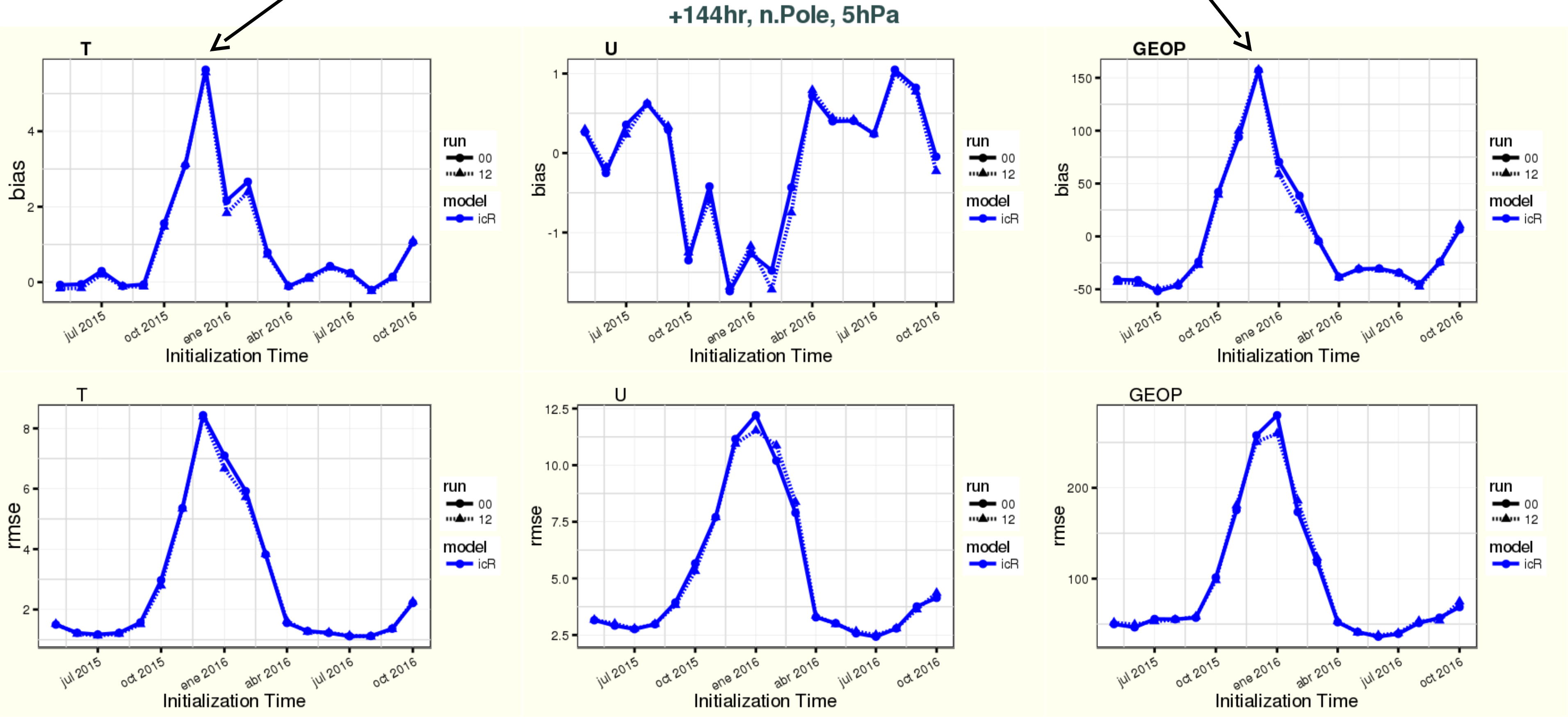
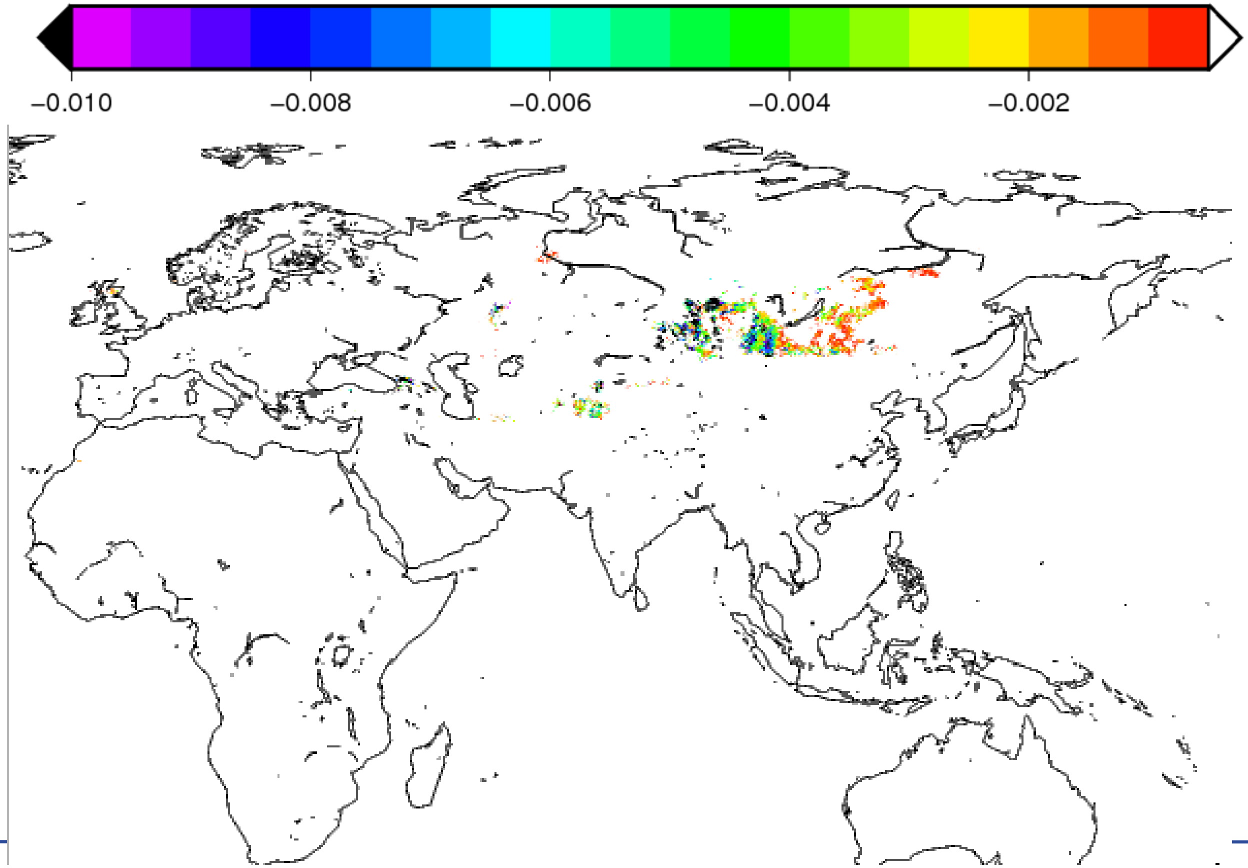
Peaks of temperature and geoptential bias occur in December



Closer investigation revealed …

… that the SSO scheme occasionally produces overly large wind tendencies around and above the stratopause

Example: SSO tendency für U wind component (m/s²), level 10 (ca. 53 km), 26.11.16 12 UTC



To cure the problem …

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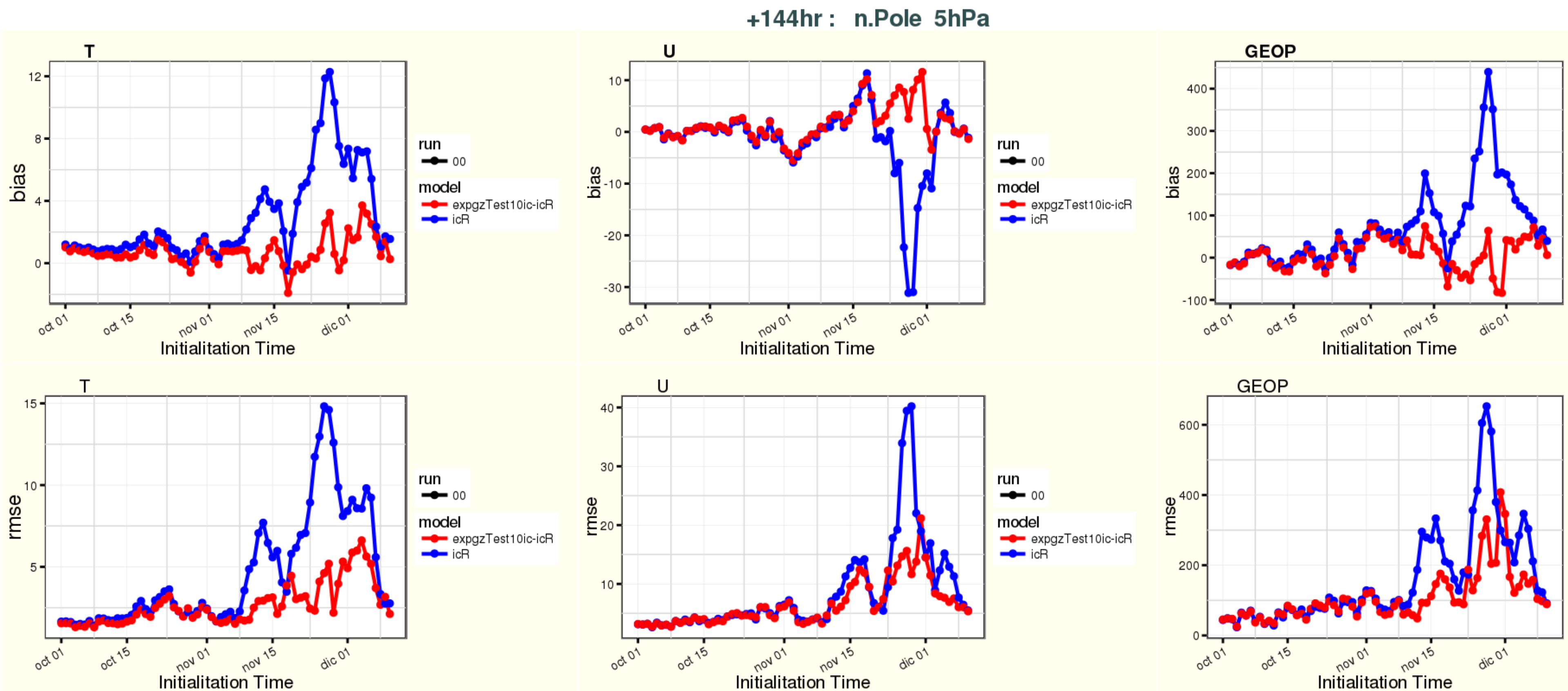
Limit the SSO wind tendencies above ~ 40 km, motivated by the fact that primary mountain waves usually don‘t reach the stratopause/mesosphere

Red: Experiment with SSO tendency limiter (Oct 1 – Dec 15, 2016)

Blue: reference



Monthly verification, May 2015 – Sep 2019

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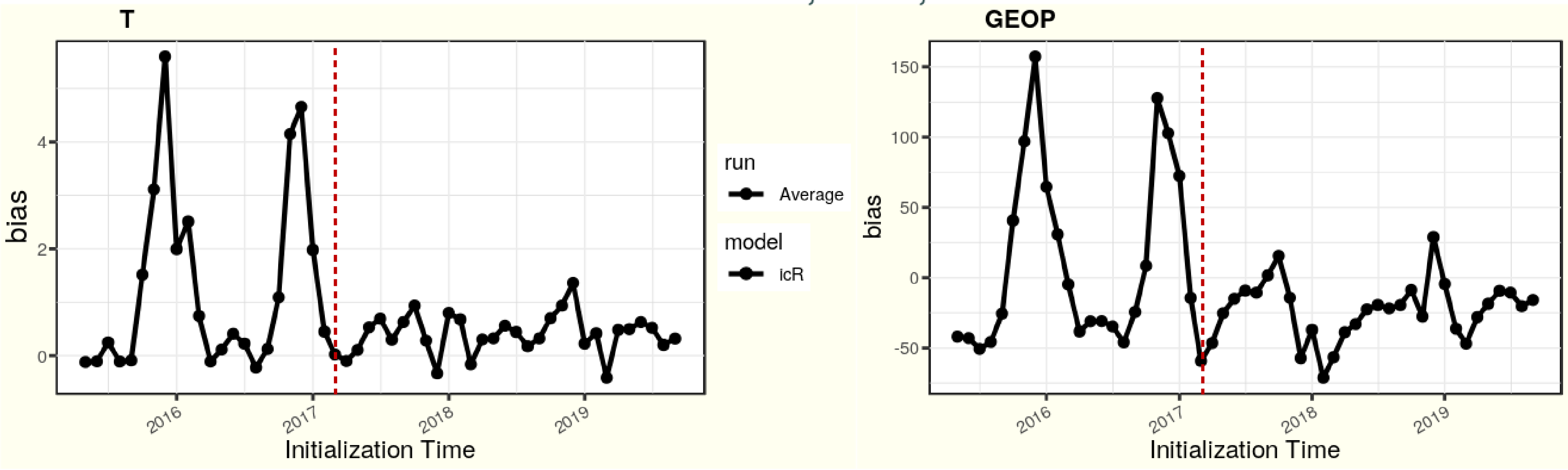
Evidently, temperature biases in the Arctic stratosphere have become acceptable after introducing the SSO tendency limiter

+144hr, n.Pole, 5hPa

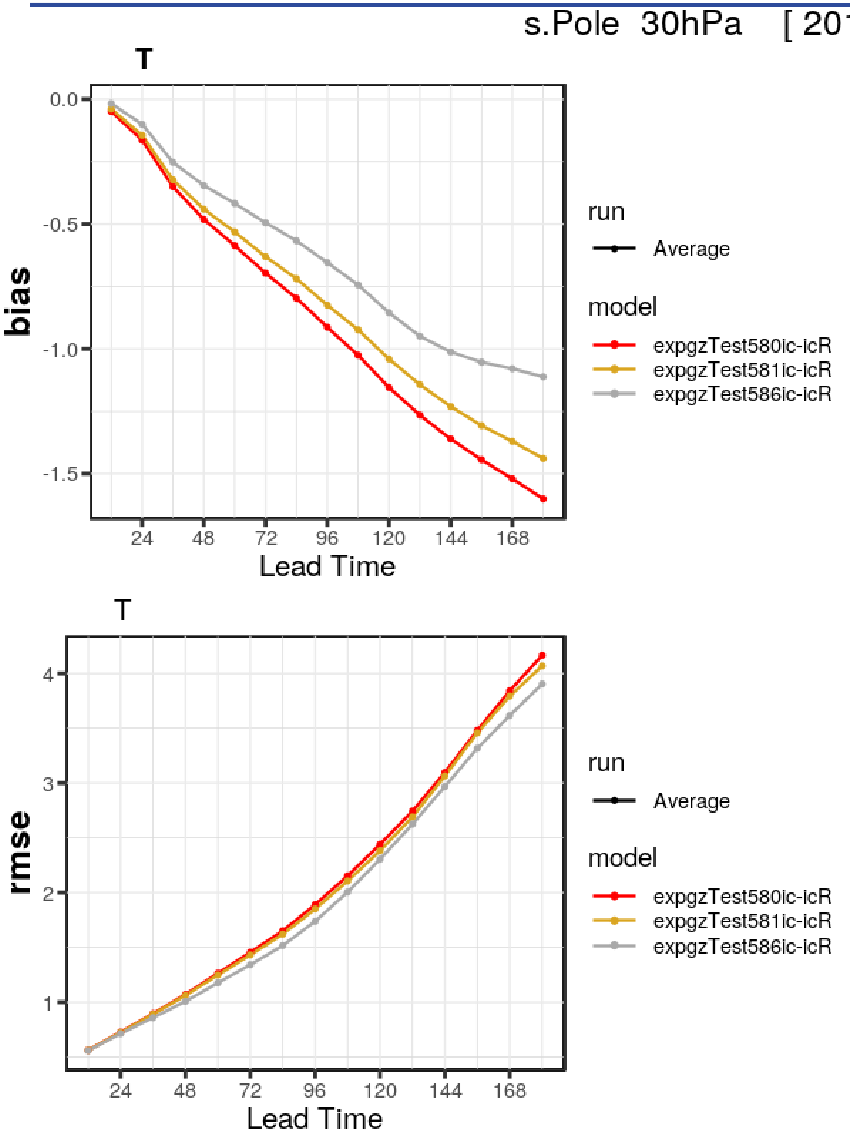


Recent/ongoing work on further reducing the cold bias in the Antarctic stratosphere

- Motivated by the lack of in-situ (radiosonde) data with sufficient quality, we use a relaxation towards climatological values for stratospheric humidity
- This works apparently well in most regions but leads to a premature moistening of the Antarctic lower stratosphere after the end of the polar night
- Thus, we plan to turn off the climatology-relaxation in this region

- In the context of the related experiments, a need for retuning the non-orographic GWD scheme became apparent (i.e. increasing the source strength to the IFS default)

Analysis verification for Antarctica at 30 hPa, Sep/Oct 2018



Reference

Modified climatology relaxation

Increased GWD forcing

Analysis verification for Antarctica at 5 hPa, Sep/Oct 2018

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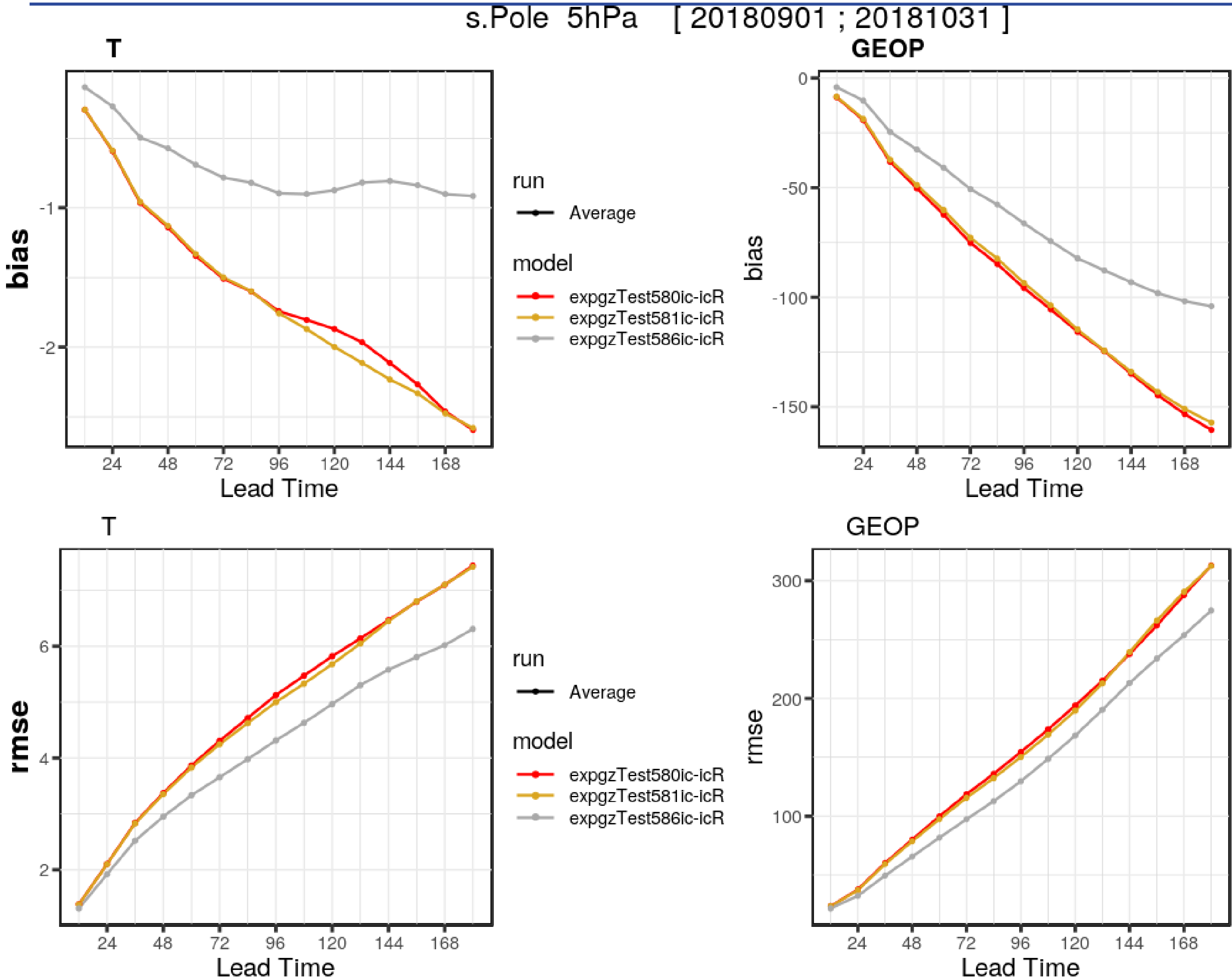

Reference

Modified climatology relaxation

Increased GWD forcing

Upper-atmosphere extension of ICON

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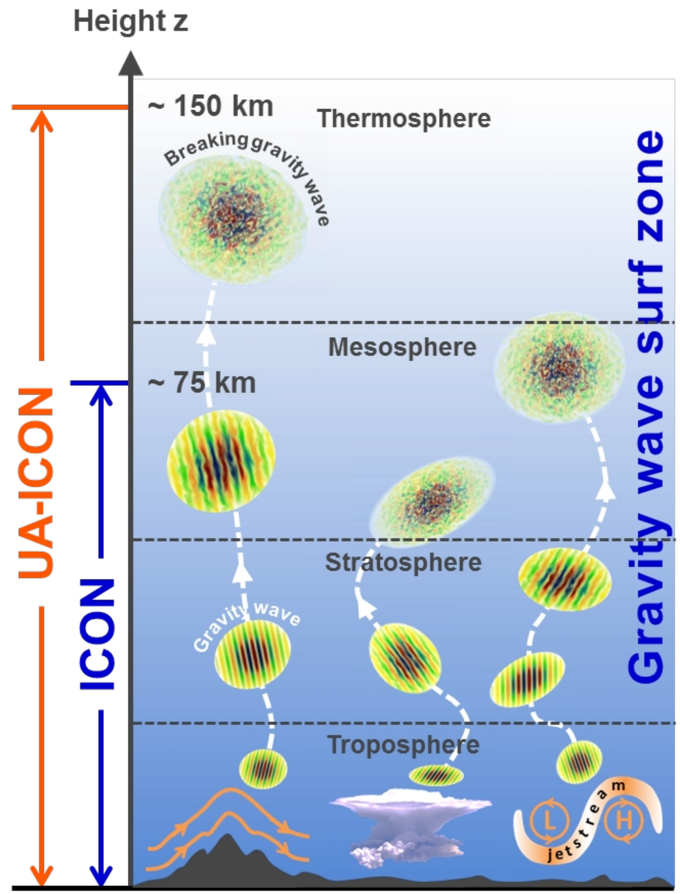
- ➔ Sub-project of DFG research group: MultiScale dynamics of Gravity Waves*
- ➔ Collaboration between Max Planck Institute for Meteorology (Hamburg) and German Weather Service
- ➔ Motivation (example): explicit simulation of gravity wave life cycle (radiation, propagation, breaking)
  $\Rightarrow$ effects on large-scale circulations from synoptic up to climatological (time) scales
- ➔ Upper-atmosphere configuration: UA-ICON
  - ➔ Upper-atmosphere physics package
  - ➔ Deep-atmosphere dynamics



More details on UA-ICON can be found in:

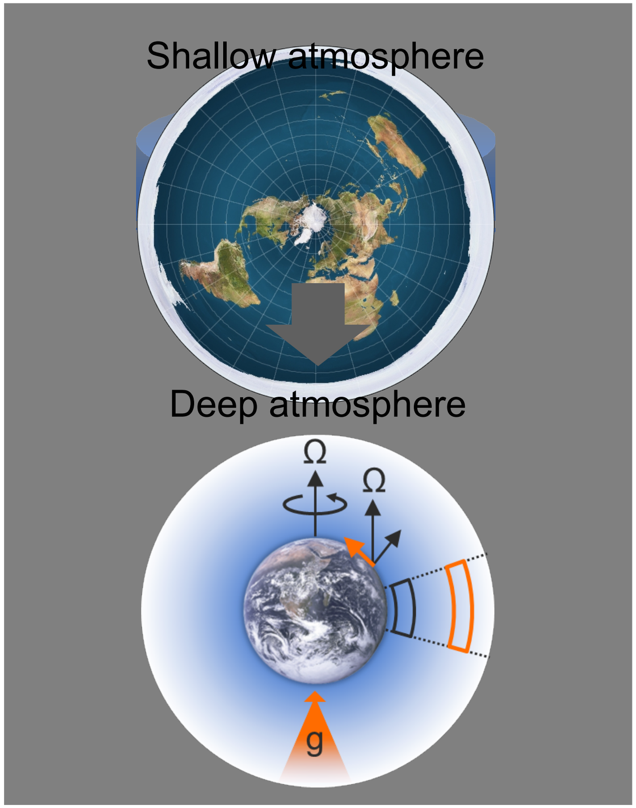
Borchert, Zhou, Baldauf, Schmidt, Zängl, Reinert (2019) ***The upper-atmosphere extension of the ICON general circulation model (...)*****, GMD**

* https://ms-gwaves.iau.uni-frankfurt.de/

Deep-atmosphere modification

➔ Shallow-atmosphere approximation
- ➔ Standard configuration of ICON
- ➔ Geometrically, the atmosphere is "plane" *

➔ Deep-atmosphere modification
- ➔ Increase of grid cell extension with height
- ➔ Consider Coriolis acceleration due to $\mathbf{\Omega}_h$
- ➔ Gravitational field strength $|\mathbf{g}|$ decreases with height



* See, e.g., *Thuburn & White (2013) Q. J. R. Met. Soc*. for geometric implications of shallow-atmosphere approximation.

Upper-atmosphere physics

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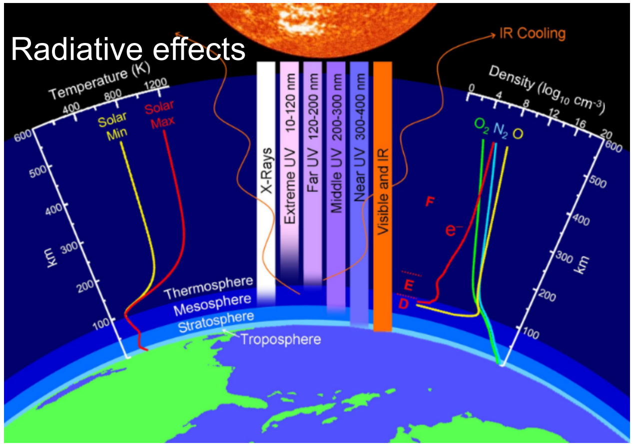
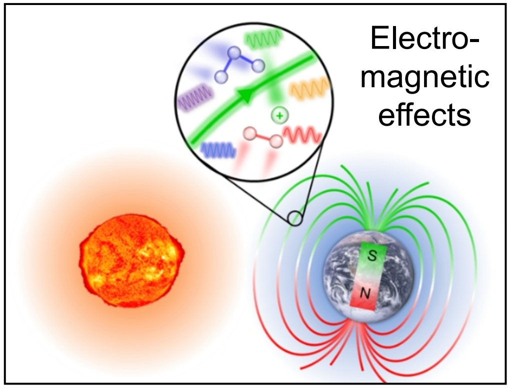
➔ Developed by our project partners: Guidi Zhou[1] and Hauke Schmidt with assistance from their Colleagues at MPI-M

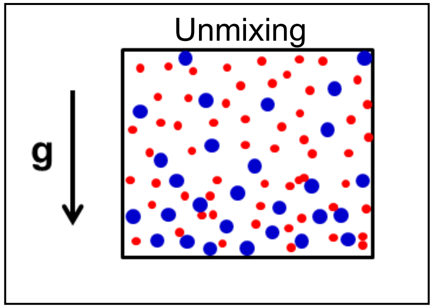


*

➔ Parameterizations mostly adopted from the chemistry climate model HAMMONIA** and modified for ICON

➔ Includes ion drag, Joule and frictional heating, molecular diffusion, and several extensions to radiative transfer including non-LTE infrared cooling





[1] Currently at College of Oceanography, Hohai University, Nanjing, China * Source: science.nasa.gov
** Upper-atmosphere extension of general circulation model ECHAM, see *Schmidt et al. (2006) J. Climate*

Further model development activities in the DFG research group

- ➔ Development of a ray-tracing based parameterzation for transient gravity waves, e.g. induced by convection
- ➔ 1D variant is already implemented in ICON and successfully applied
- ➔ Full 3D parameterization is under development

- ➔ See posters by Kim et al.: *Convective Gravity Waves Modeled by a Transient Gravity-Wave Parameterization in ICON*

  and by Bölöni et al.: *Towards a transient gravity wave drag parametri-zation in atmospheric models*

- ➔ More details on the underlying theory on Thursday morning by Ulrich Achatz

Summary

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- Systematic improvements in the specification of the ozone field, moisture analysis / cross-tropopause moisture transport, and gravity-wave forcing helped reducing our stratospheric temperature (and wind) errors during the last years
- However, it is difficult to detect an impact on tropospheric fore-cast quality for our (relatively short) forecast range of 7.5 days

Activities in our ongoing DFG research group:

- Extension of ICON dynamics and physics for applications in the upper atmosphere
- Development of a novel parameterization for transient gravity waves including 3D propagation

Additional slides

Upper-atmosphere physics: references

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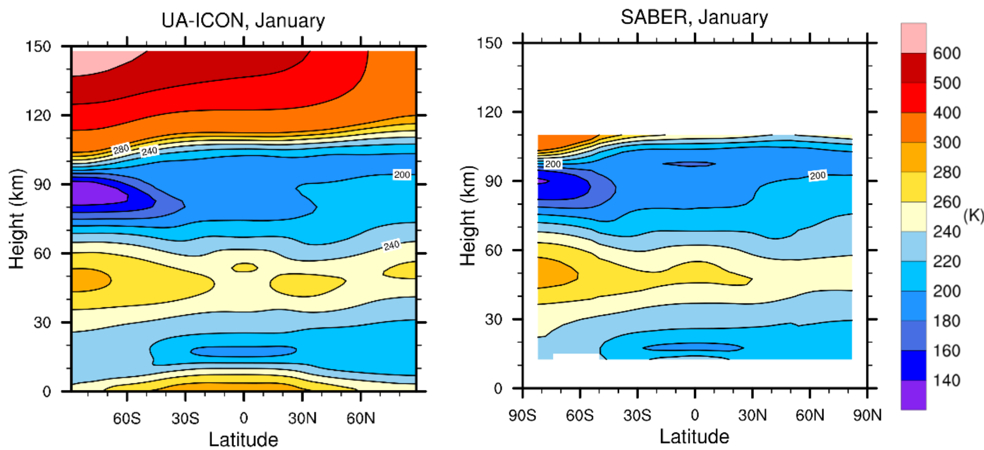
Dissipative effects of neutral and ionized components	Reference
Molecular diffusion	Huang et al. (1998); Banks & Kockarts (1973)
Frictional heating	Gill (1982)
Ion drag & Joule heating	Hong & Lindzen (1976)

Radiative effects	Reference
Schumann-Runge bands & continuum (O_2)	Strobel (1978)
Extreme ultraviolet (N_2, O, O_2)	Richards et al. (1994)
Non-local-thermodynamic-equilibrium infrared cooling (CO_2, NO, O_3)	Fomichev & Blanchet (1995); Fomichev et al. (1998)
NO infrared cooling	Kockarts (1980)
Chemical heating	Climatology from HAMMONIA

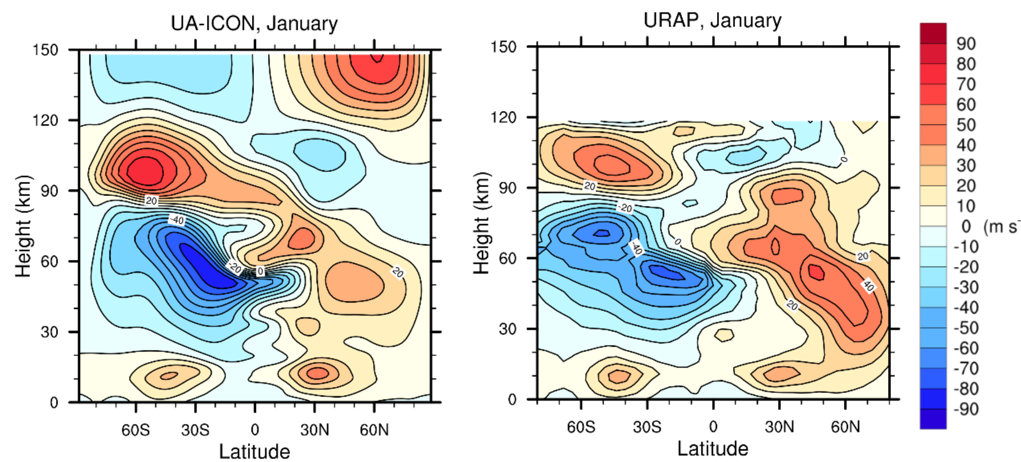
Exemplary results

- ➔ Simulation with ICON
  in ECHAM physics mode
  + upper-atmosphere physics
  + deep-atmosphere dynamics

- ➔ In general good agreement with observational products (SABER, URAP),
  but still need for tuning (e.g., strength and position of middle- and upper-atmosphere jets)



Temperature: zonally averaged ~20-year climatology *



Zonal wind component: zonally averaged ~20-year climatology *

* Source: *Borchert et al. (2019) GMD*