CONSORTIUM FOR SMALL SCALE MODELING COSMO

Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DWD

Recent numerics developments in the COSMO model

40th EWGLAM / 25th SRNWP-meeting
Salzburg
01-04 Oct. 2018

Michael Baldauf (DWD),
Bogdan Rosa, Zbigniew Piotrowski, Damian Wojcik (IMGW),
Andreas Will, Jack Ogaja (Univ. Cottbus),
Werner Schneider (Univ. Bonn)

COSMO Science Plan (2015-2020)

main topics for COSMO dynamics

- for current 'Runge-Kutta' split-explicit dynamical core (*Wicker, Skamarock (2002), Baldauf (2010), …*)
  - Extension of the new *Bott (2010)* tracer advection scheme by LTS
  - Higher order, symmetric scheme for the horizontal discretizations (*Morinishi et al. (1998) JCP, Ogaja, Will (2014) MetZ*)
  - improve Mahrer discretiz. for better tolerance of steep terrain
  - …
- Eulag dynamical core (*Smolarkiewicz et al. …*) as an alternative option
  Priority Projects 'CELO', 'EX-CELO', 'CEL-ACCEL', 'CCE'
- transition from COSMO model → ICON (LAM) model (~2020+)
  PP 'Comparison of the dynamical cores of ICON and COSMO' (CDIC)
  PP 'Transition of COSMO to ICON-LAM' (C2I) → talk by Daniel Rieger

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The new Bott advection scheme

… as an *optional* candidate for tracer advection

Andreas Bott,
Werner Schneider (Univ Bonn),
Uli Blahak,
Michael Baldauf (DWD)

$$\frac{\partial \rho q}{\partial t} + \nabla \cdot (\mathbf{v} \rho q) = \rho S$$

COSMO-…: $q = q_v, q_c, q_i, q_r, q_s, q_g, (TKE)$

Original COSMO-implementation (by W. Schneider, modif. by U. Blahak):
verification results see last SRNWP/EWGLAM meeting

in the meanwhile: problems found with
reproducibility under domain decomposition; accuracy → …

Bott (2010) Atm. Res.

to reduce splitting errors in strongly deformational fields,
add and subtract the divergence term (‚deformational correction'):

$$\begin{aligned}
\phi' &= \phi^n - \Delta t \, \frac{f_x^+(\phi^n) - f_x^-(\phi^n)}{\Delta x} + \Delta t \, \phi^n \frac{\partial u}{\partial x}, \\
\phi'' &= \phi' - \Delta t \, \frac{f_y^+(\phi') - f_y^-(\phi')}{\Delta y} + \Delta t \, \phi^n \frac{\partial v}{\partial y}, \\
\phi^{n+1} &= \phi'' - \Delta t \, \frac{f_z^+(\phi'') - f_z^-(\phi'')}{\Delta z} + \Delta t \, \phi^n \frac{\partial w}{\partial z} - \Delta t \, \phi^n \nabla \cdot \mathbf{v},
\end{aligned}$$

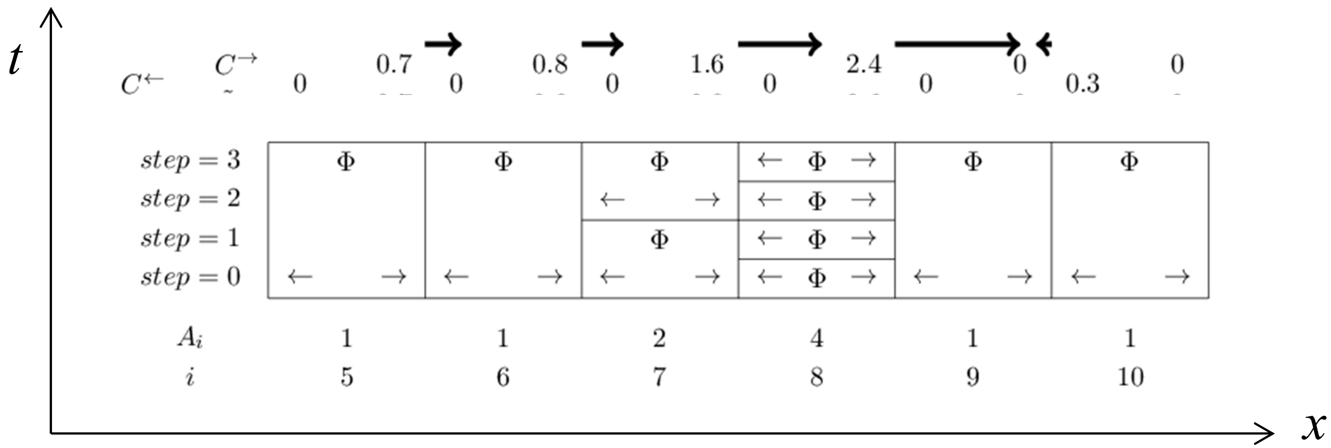
- scheme is (still) locally mass conserving
- scheme can be formulated positive-definite
- ϕ=const. remains constant in arbitrary divergence free wind fields (*Bott (2010)* calls this ‚mass-consistent')
- use e.g. *Bott (1989) MWR* to calculate fluxes f_x, f_y ,f_z.
- for CFL>1: ‚row-oriented time stepping' → problems with reproducibility

New idea: local time stepping

developed in a way that:

- it maintains mass conservation exactly
- it is positive definite (up to ‚machine precision')
- it maintains the ‚Bott (2010)-mass-consistency' property

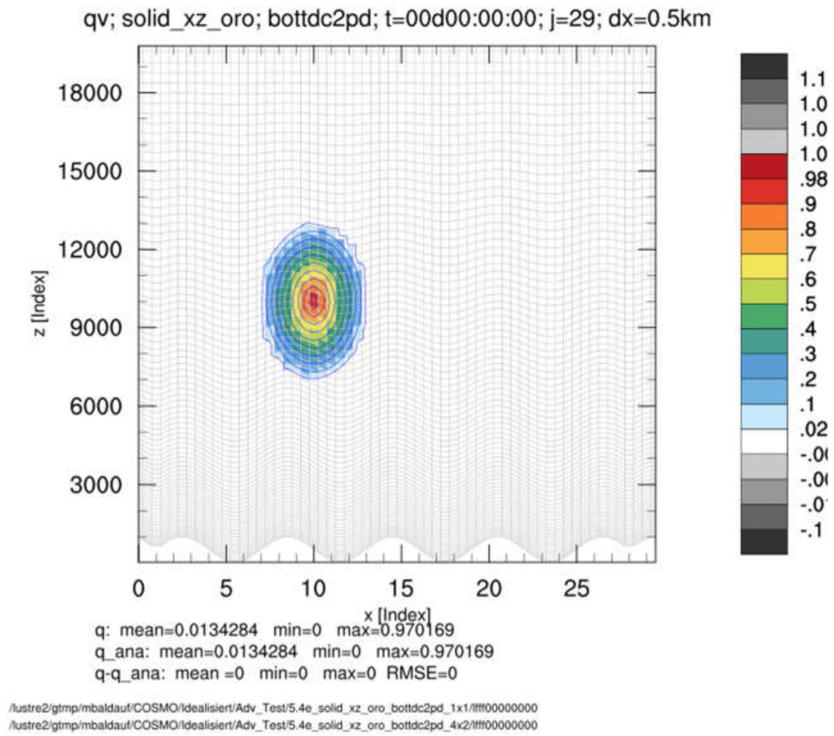
→ simple Strang-splitting is possible → **larger saving of computation time!**



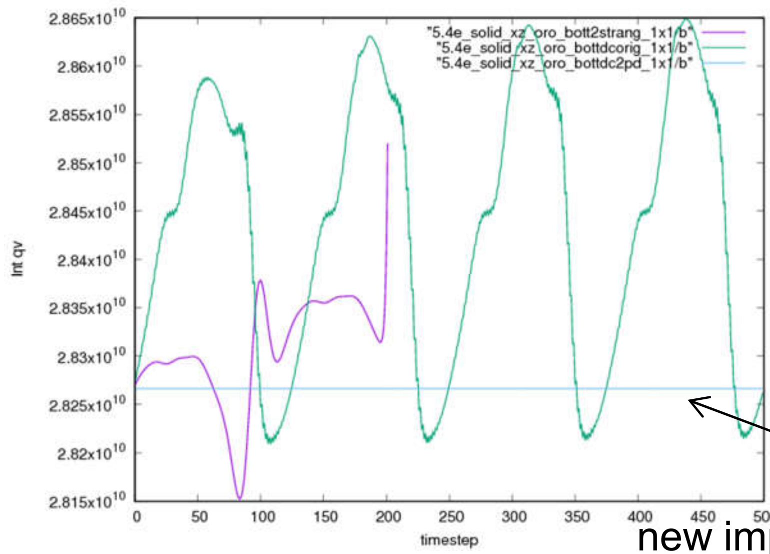
Baldauf: Local time stepping for a mass-consistent and time-split advection scheme (accepted after rev. by QJRMS)

Idealized advection tests performed
(this is at the same time a contribution to the PP CDIC Task 1, advection tests)

1.) solid body rotation in x-y- and x-z- plane, with/without orography



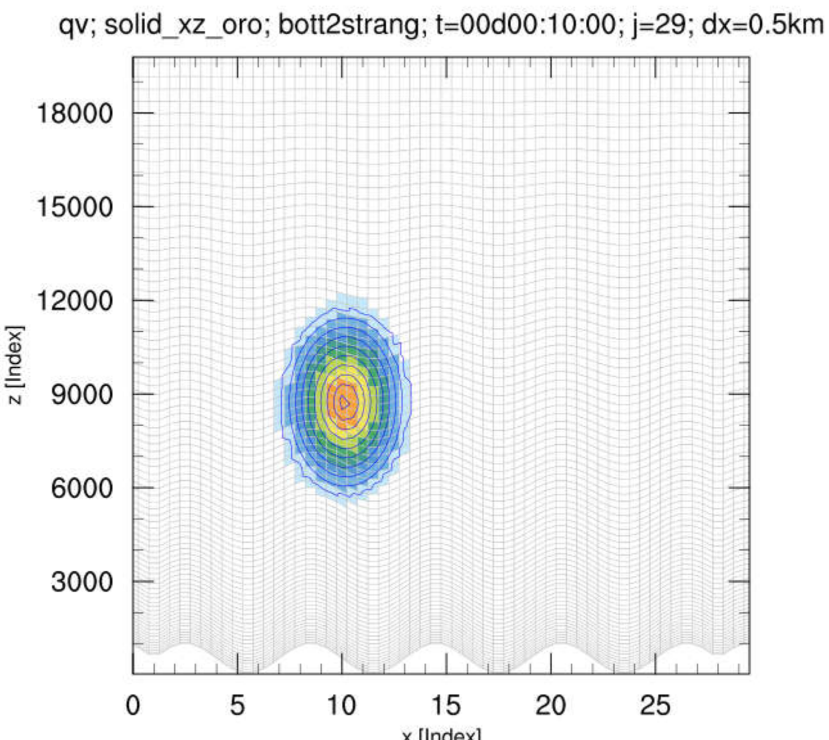
total mass:



new implementation
is exactly
mass conserving

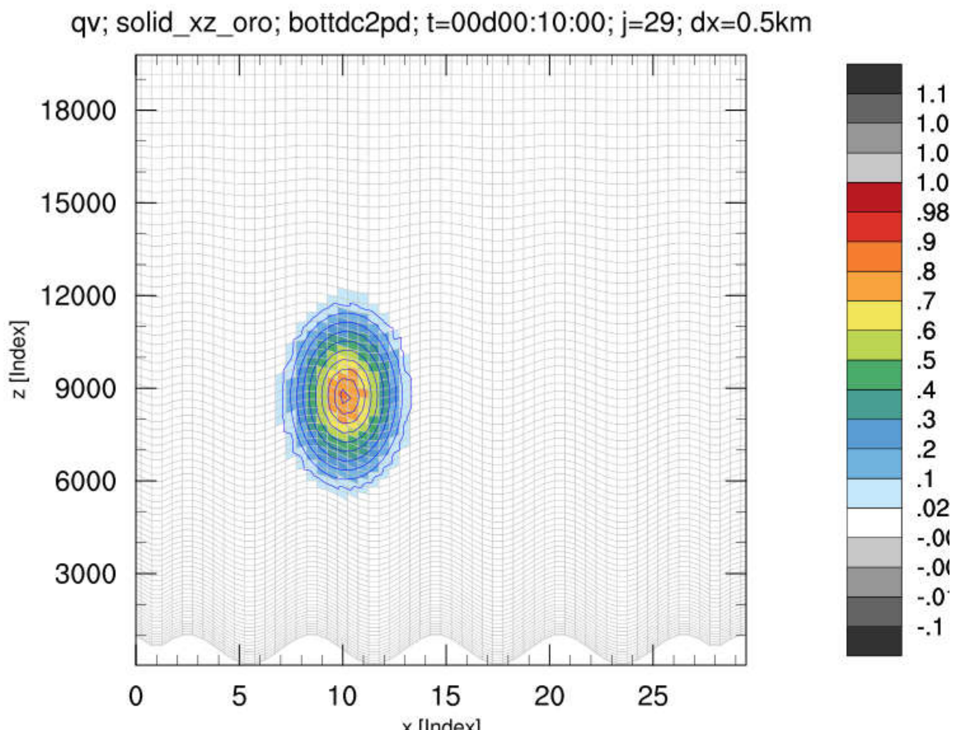
1.) solid body rotation in x-z- plane, with orography

solution after one rotation:



q: mean=0.0143835 min=-1.6724e-14 max=0.799932
q_ana: mean=0.0143537 min=0 max=0.939292
q-q_ana: mean =2.98235e-05 min=-0.13936 max=0.05968 RMSE=0.00673

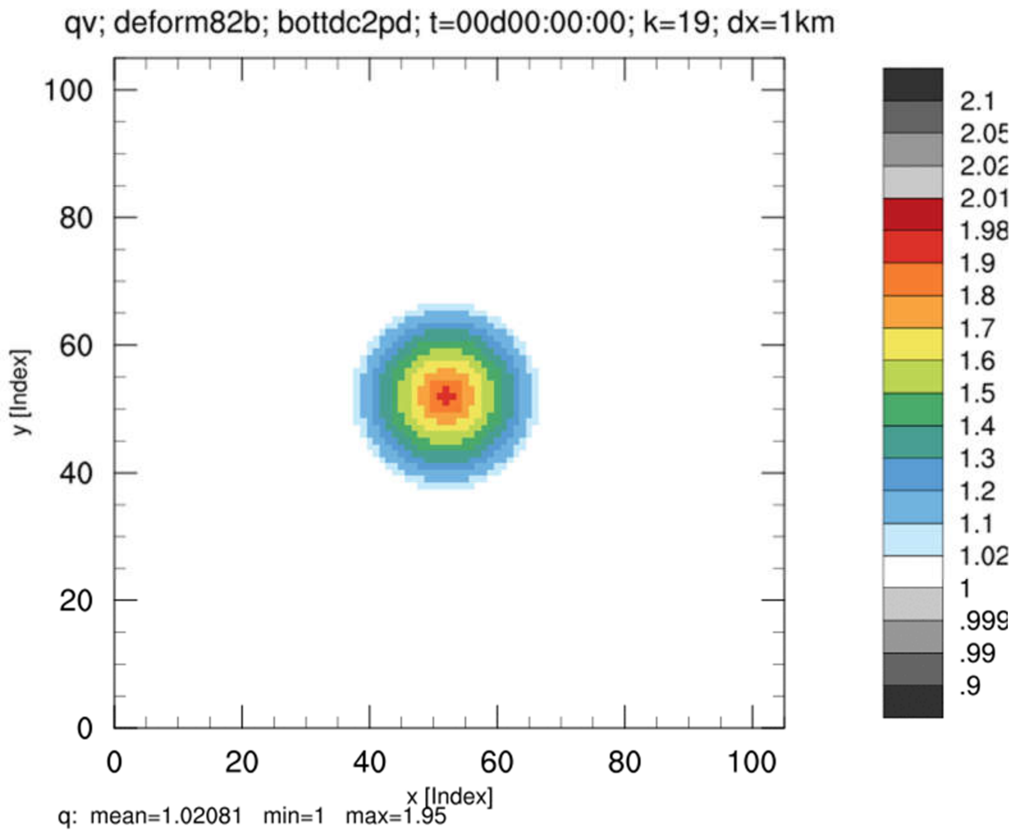
/lustre2/gtmp/mbaldauf/COSMO/Idealisiert/Adv_Test/5.4e_solid_xz_oro_bott2strang_1x1/lfff00001000
/lustre2/gtmp/mbaldauf/COSMO/Idealisiert/Adv_Test/5.4e_solid_xz_oro_bott2strang_4x2/lfff00001000

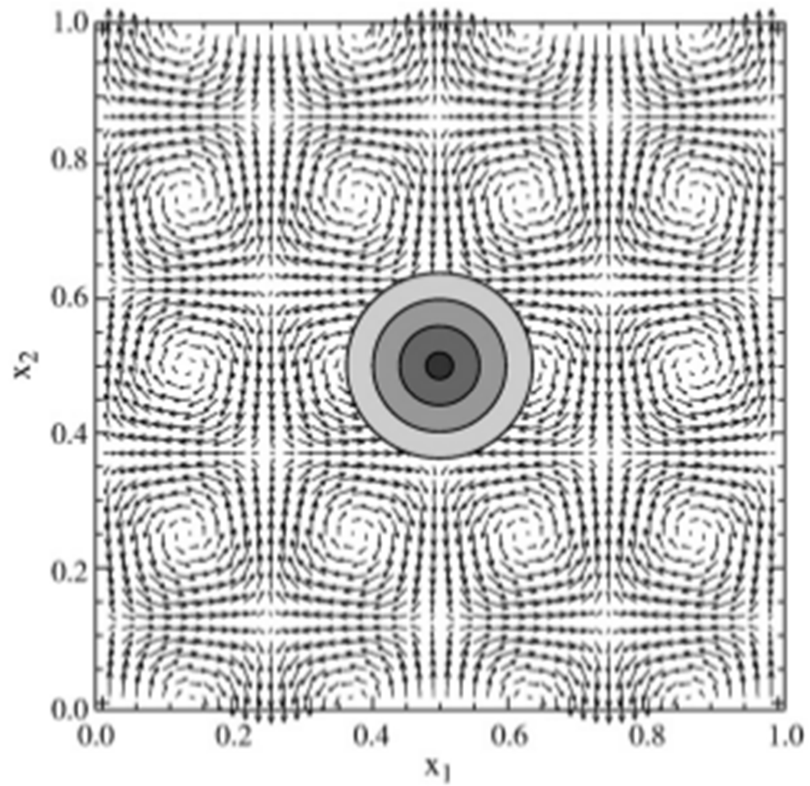


q: mean=0.0143229 min=-3.73214e-19 max=0.801934
q_ana: mean=0.0143537 min=0 max=0.939292
q-q_ana: mean =-3.07644e-05 min=-0.137359 max=0.0602573 RMSE=0.00641114

/lustre2/gtmp/mbaldauf/COSMO/Idealisiert/Adv_Test/5.4e_solid_xz_oro_bottdc2pd_1x1/lfff00001000
/lustre2/gtmp/mbaldauf/COSMO/Idealisiert/Adv_Test/5.4e_solid_xz_oro_bottdc2pd_4x2/lfff00001000

Strongly deformational flow test (*Smolarkiewicz, 1982*)





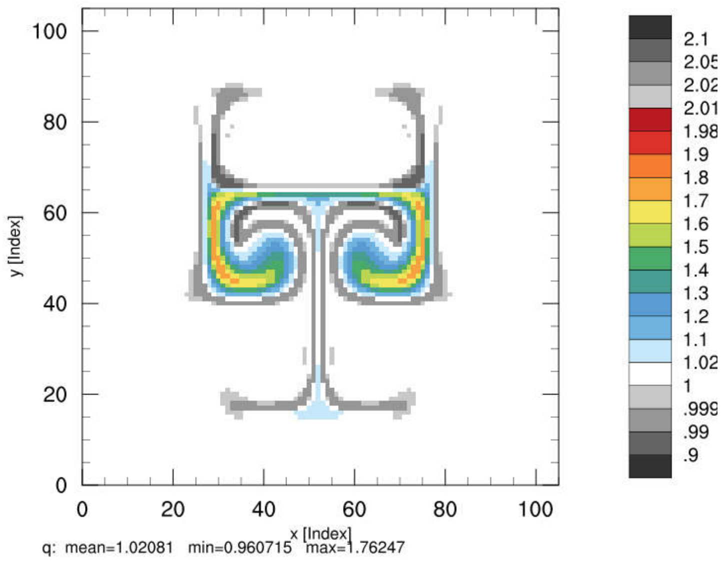
from Bott (2010)

/lustre2/gtmp/mbaldauf/COSMO/Idealisiert/Adv_Test/5.4e_deform82b_bottdc2pd_1x1/lfff00000000.nc

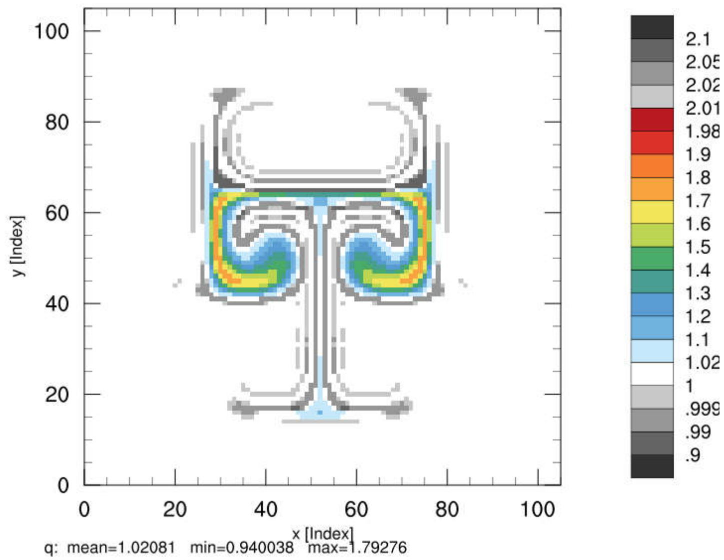
velocity field with $du/dx + dv/dy = 0$
but the two terms are strongly non-zero.
→ can lead to splitting errors

Strongly deformational flow test (Smolark. 1982), after t=5 min

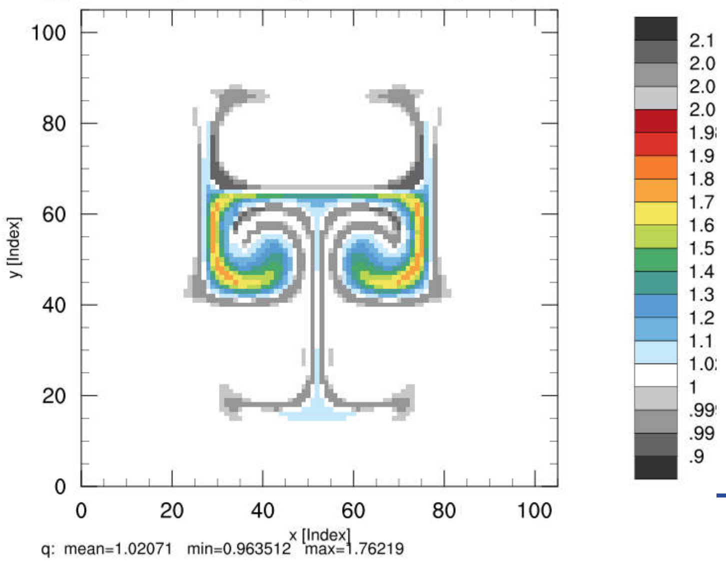
new version: `BottDC2`



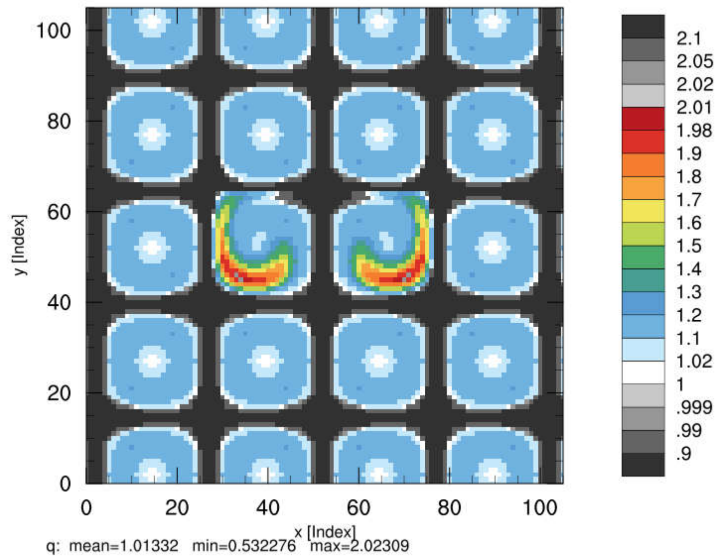
Bott (2010) Univ. Bonn version



current version: `Bott2_Strang`



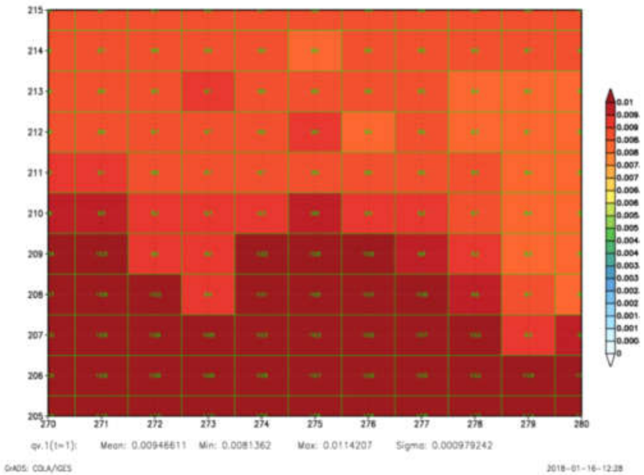
Bott (1989)



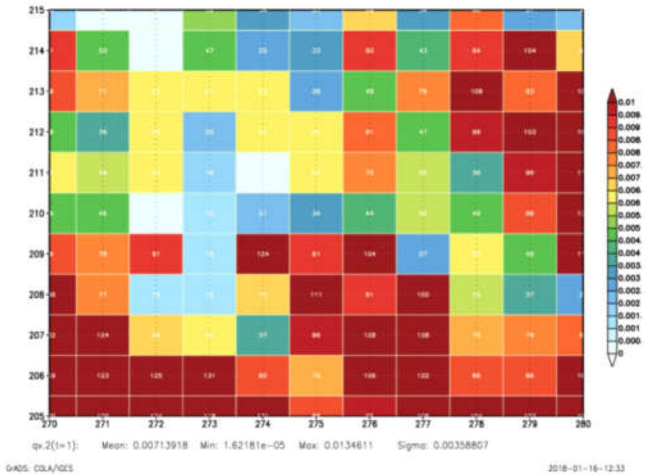
Again: mass-consistency

Problem: the mass-conserving version shows an emptying of grid cells near the ground:

current scheme in COSMO:



new mass-conserving version:



Reason: since the COSMO dyn. core is not mass-conserving, there is a need to improve **mass-consistency**:
Solve an (artificial) continuity equation for ρ by the new scheme and calculate tracer concentration q after the advection step.
Unfortunately, this methodology **destroys exact mass-conservation**

New operational setup COSMO-D2

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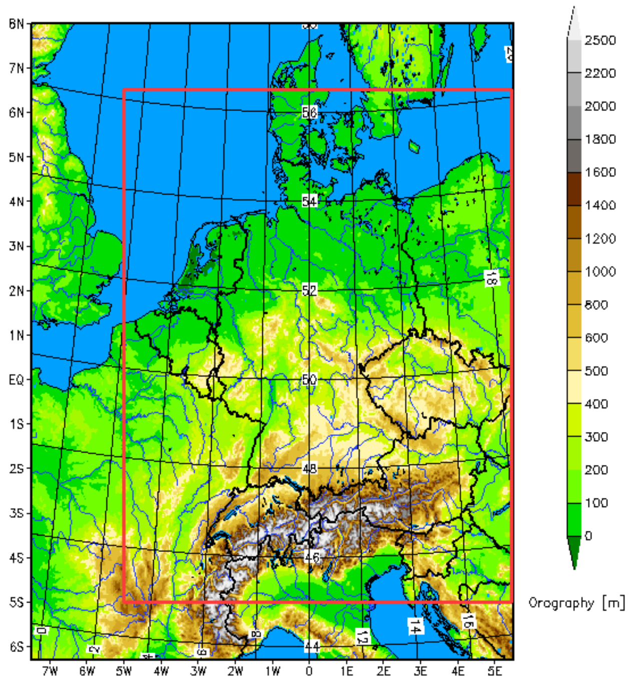
At DWD, **COSMO-D2** has replaced **COSMO-DE**
with the following changes **since 15 May 2018**:

➔ increase horizontal resolution from 2.8 km to 2.2 km

➔ increase number of vertical levels from 50 to 65

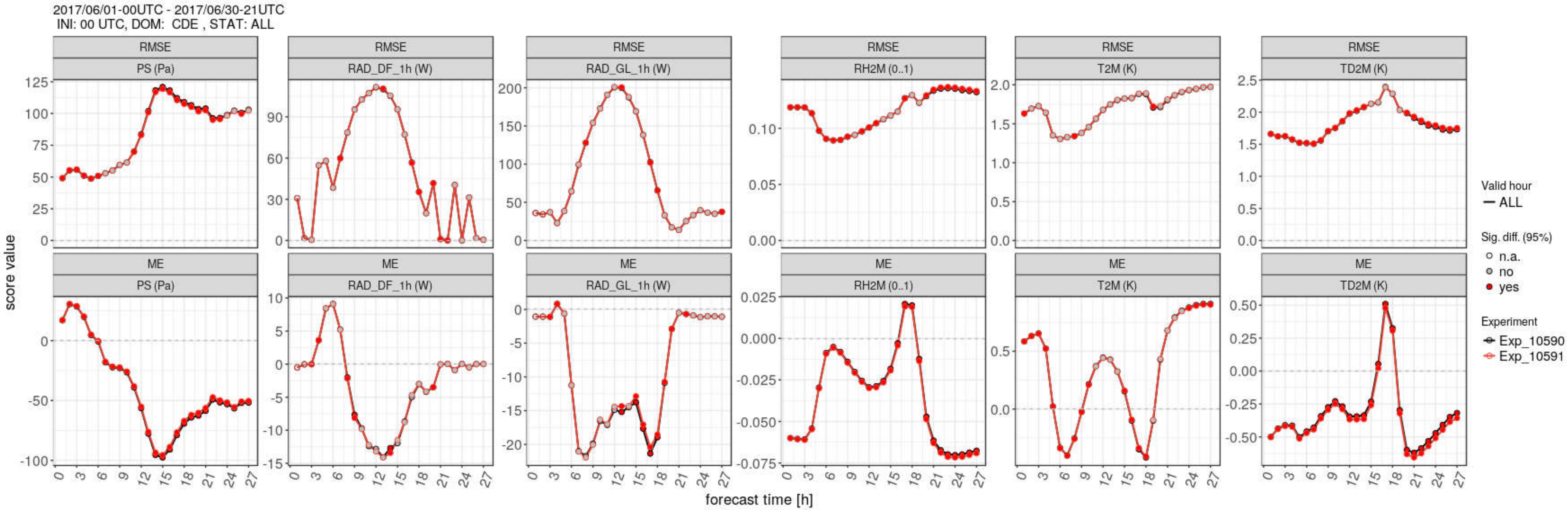
➔ increase area from 10.5° * 11.5° to 13° * 14.3°



COSMO-D2: 651 * 716 * 65 GPe
1440 * 1590 * 22 km³

COSMO-DE: 421 * 461 * 50 GPe
1160 * 1280 * 22 km³

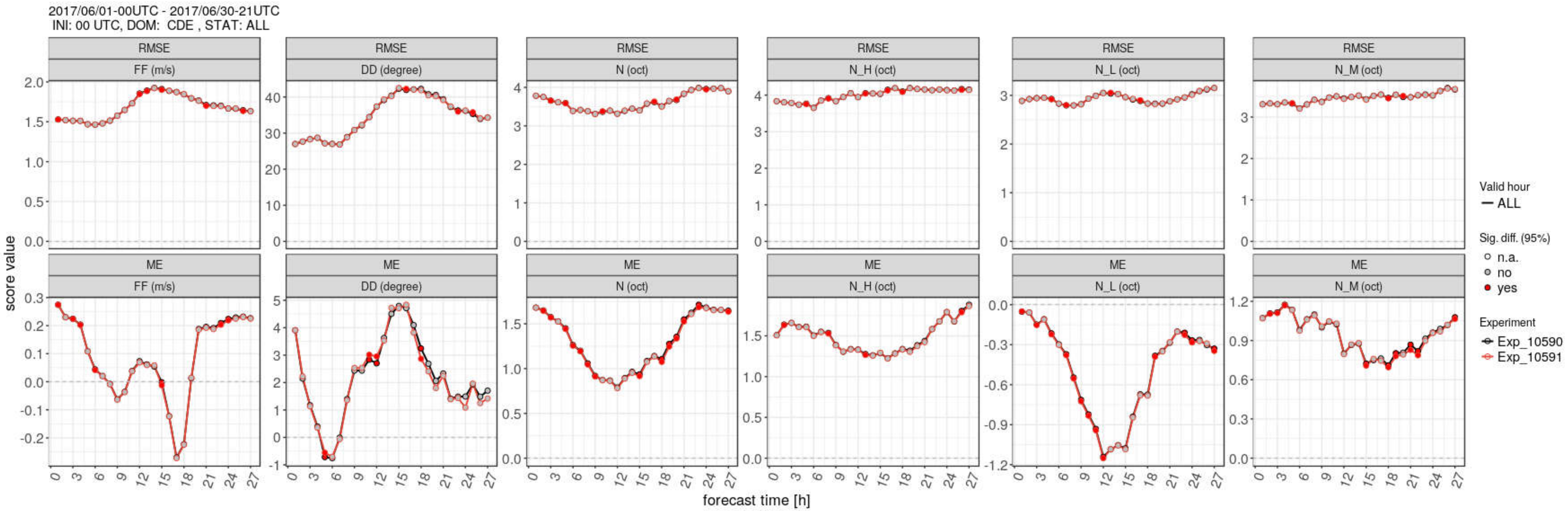
Synop-Verification, cont., June 2017



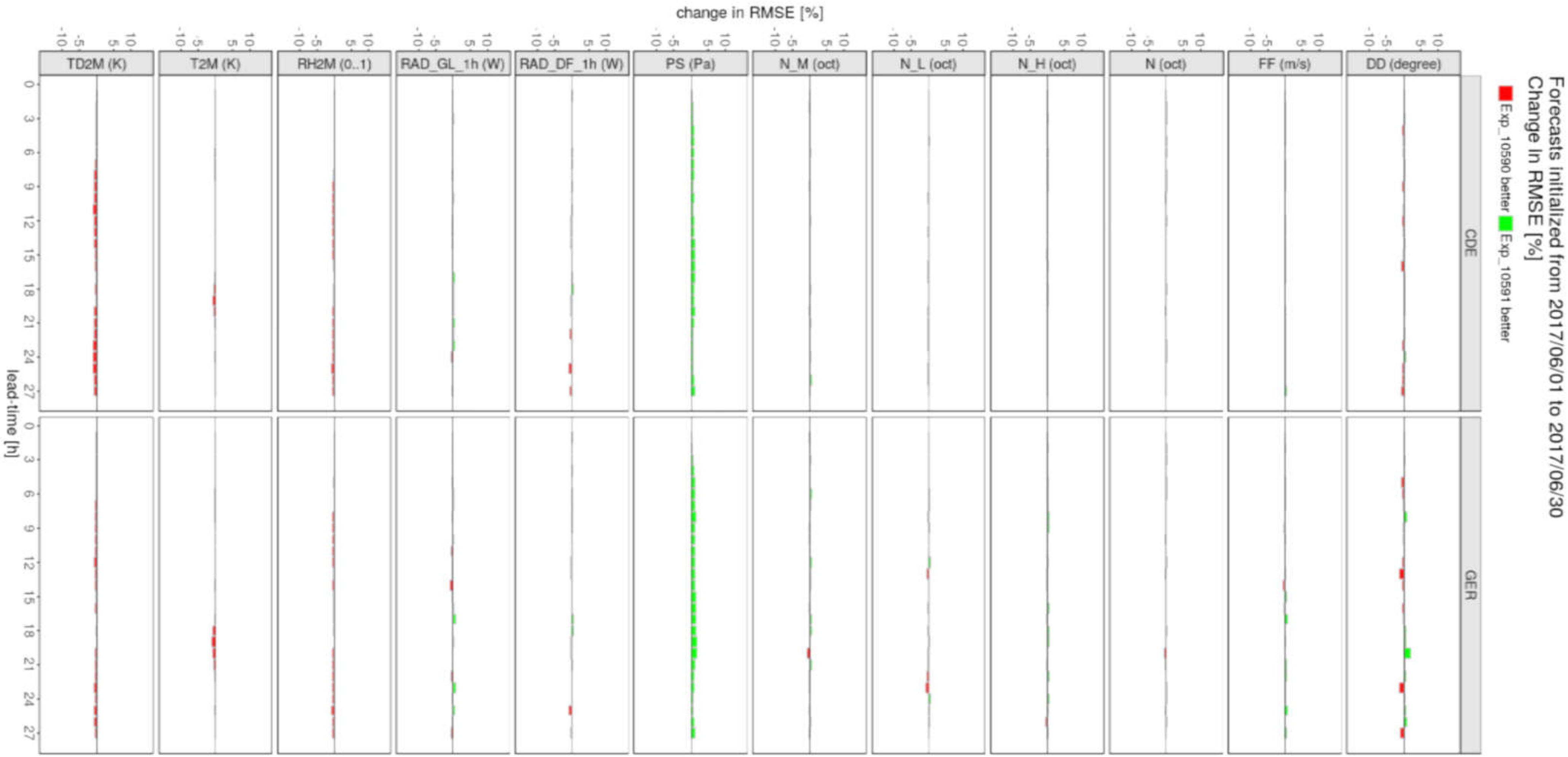
Exp. 10590: y_scalar_advect=„BOTT2_Strang“ (current scheme)
Exp. 10591: y_scalar_advect=„BOTTDC2“ (new scheme)

based on COSMO 5.4h1
only COSMO-D2 forecast runs; every run is initialized by analyses of NUMEX-Exp. 10535 (‚COSMO-D2 reforecasts‘).

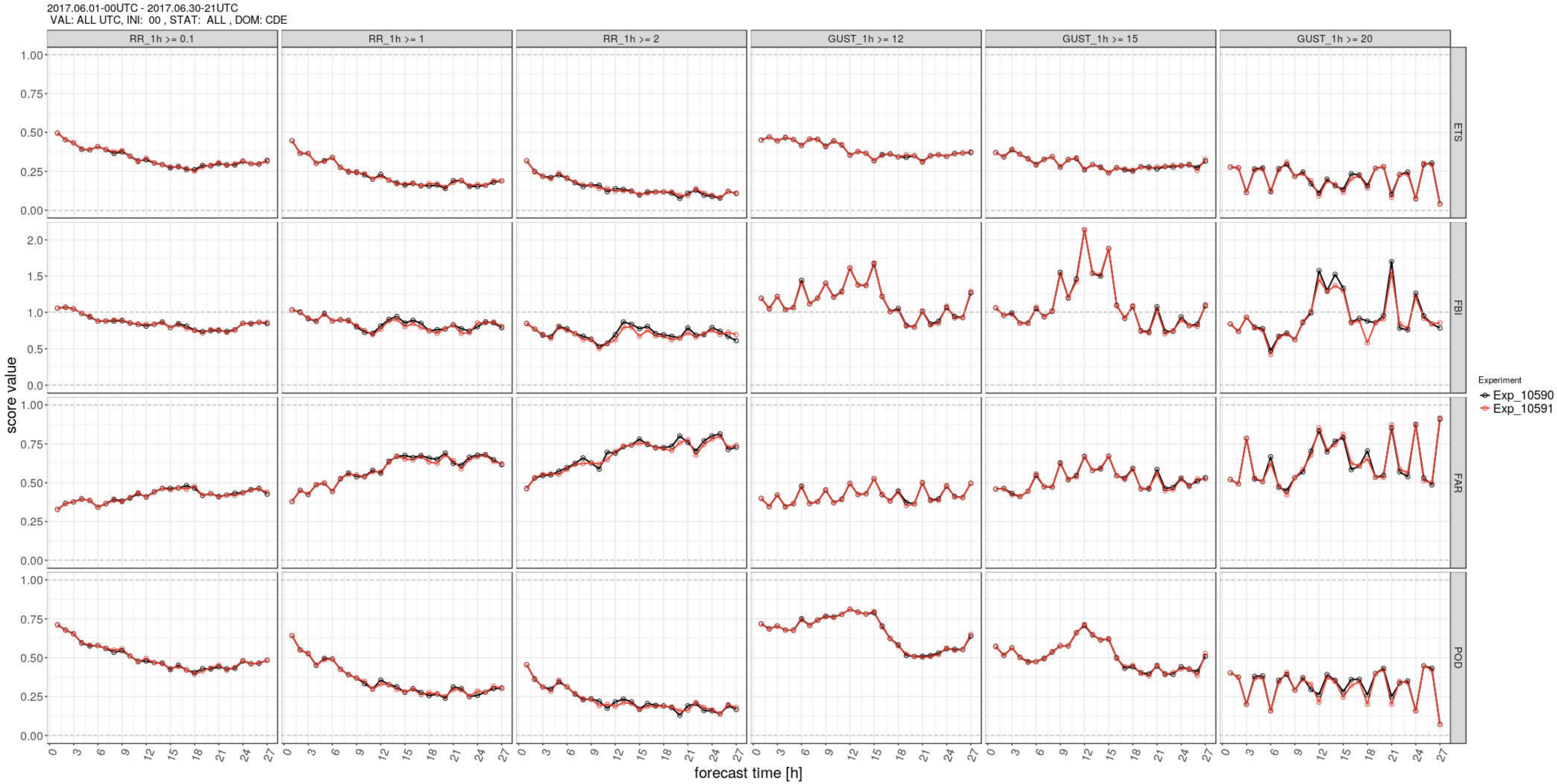
Synop-Verification, cont., Juni 2017



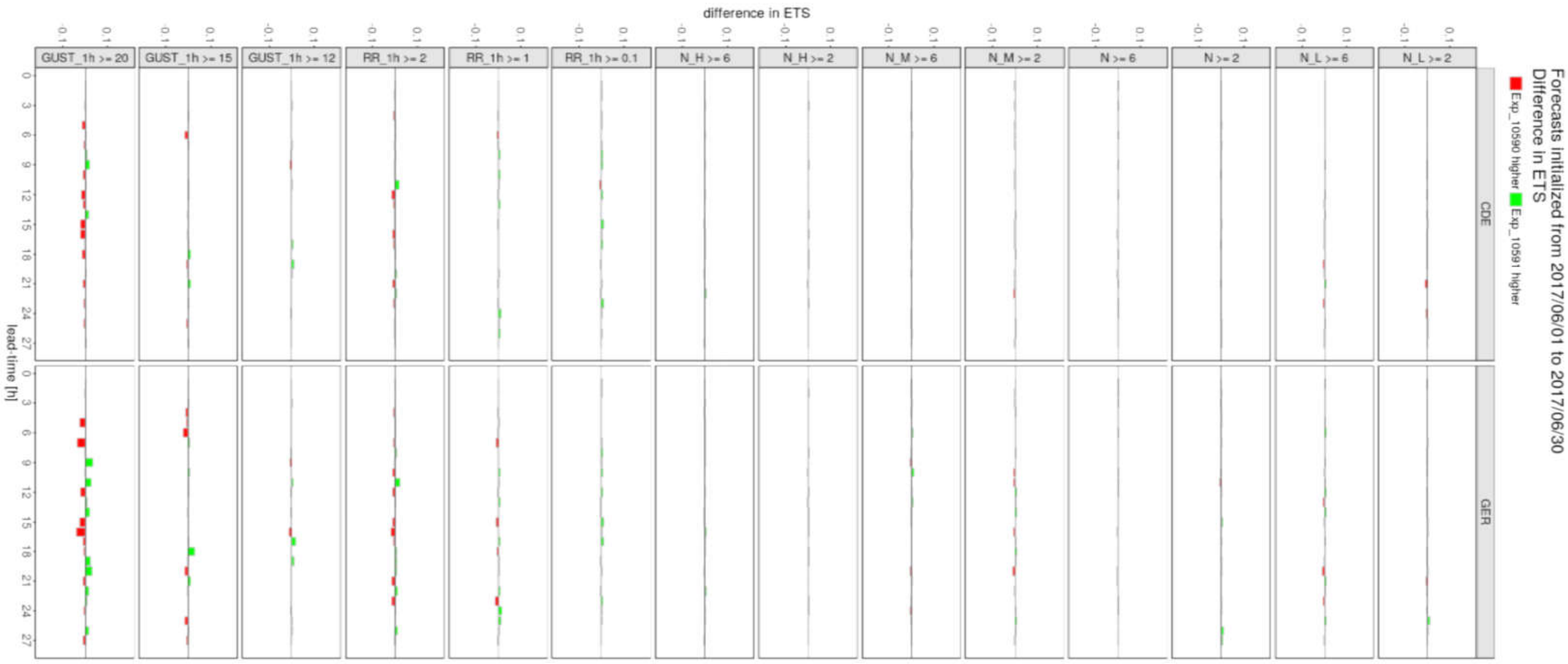
Synop-Verification, cont., Juni 2017

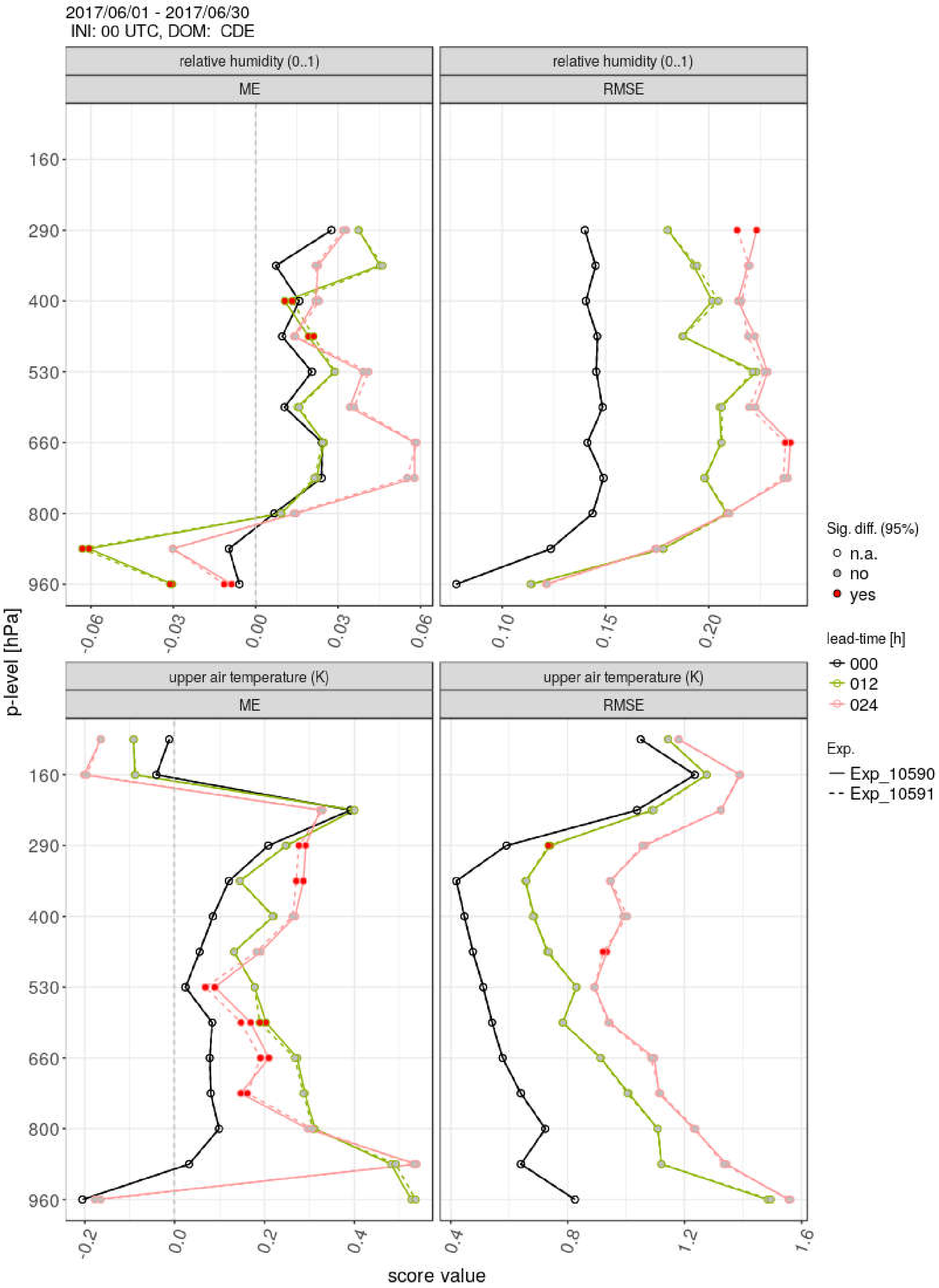


Synop-Verification, categ., Juni 2017



Synop-Verification, categ., Juni 2017





2017/06/01 - 2017/06/30
INI: 00 UTC, DOM: CDE
relative humidity (0..1)
ME
relative humidity (0..1)
RMSE
upper air temperature (K)
ME
upper air temperature (K)
RMSE
p-level [hPa]
score value
Sig. diff. (95%)
n.a.
no
yes
lead-time [h]
000
012
024
Exp.
Exp_10590
Exp_10591

Summary for new tracer advection scheme

- Both idealized tests and hindcast-/Numex-experiments show that the transport properties of the new version (`y_scalar_advect=‚BOTTDC2‘`) and the current (`‚BOTT2_Strang‘`) are quite similar
  (reason: same flux formulation by *Bott (1989)*)
- The new scheme was tested with several other periods (also in full ensemble mode) and always kept stable
- The ‚deformational correction‘ (*Bott, 2010*) allows ‚simple Strang-splitting‘ and together with the (reproducible!) ‚local time stepping‘ results in a **reduction of computation time**
  - for the tracer advection alone of **about 30%**
  - and for a whole COSMO-D2 run by **about 5%.**
- Scheme is available with COSMO version 5.5a
- runs pre-operationally at DWD since 11 July 2018

Higher Order Spatial Schemes for the COSMO Model

Andreas Will, Jack Ogaja (BTU Cottbus)

New (symmetric!) discretization of the advection operator:

$$AdvS4 := \quad (\mathbf{v_h} \cdot \nabla_h u)_{i+\frac{1}{2},j} := \quad \frac{9}{8}\overline{\overline{u}^{O4,\lambda}\delta_\lambda u}^{\lambda} - \frac{1}{8}\overline{\overline{u}^{O4,\lambda}\delta_{3\lambda} u}^{3\lambda} + \frac{9}{8}\overline{\overline{v}^{O4,\lambda}\delta_\phi u}^{\phi} - \frac{1}{8}\overline{\overline{v}^{O4,\lambda}\delta_{3\phi} u}^{3\phi}$$

kinetic energy conserving discretization (*Morinishi et al., 1998*)
(Ogaja, Will (2014) MetZ)

Additionally one can use 4th order discretizations of horizontal derivatives in the fast waves solver.

In the following:
CDE011: COSMO-DE (2.8km) with original COSMO RK-scheme (C3p2d0.25Ct)
CDE012: COSMO-DE (2.8km) with symmetric discretization (S4p4d0.0Cs)

List of simulations 2000-2014

EXPID	IBC	HR	DOM	CONF
C3p2d0.25Ct-dynamics (standard COSMO-RK)				
TEU006	ERAINT	50 km	EUL	CCLM
CEU011	TEU006	7 km	EU	COSMO-EU
CDE011	CEU011	2.8km	DE	COSMO-DE
S4p4d0.0Cs-dynamics (symmetric dynamic)				
TEU007	ERAINT	50 km	EUL	CCLM
CEU012	TEU007	7 km	EU	COSMO-EU
CDE014	CEU012	4.5km	DE	COSMO-DE
CDE012	CEU012	2.8km	DE	COSMO-DE, tkhmin=tkmmin=0.01

IBC: Initial and Boundary Conditions
HR: Horizontal model resolutions
DOM: Domain simulated
CONF Model configuration used

RESULTS for WP (W>0)
mean 2000

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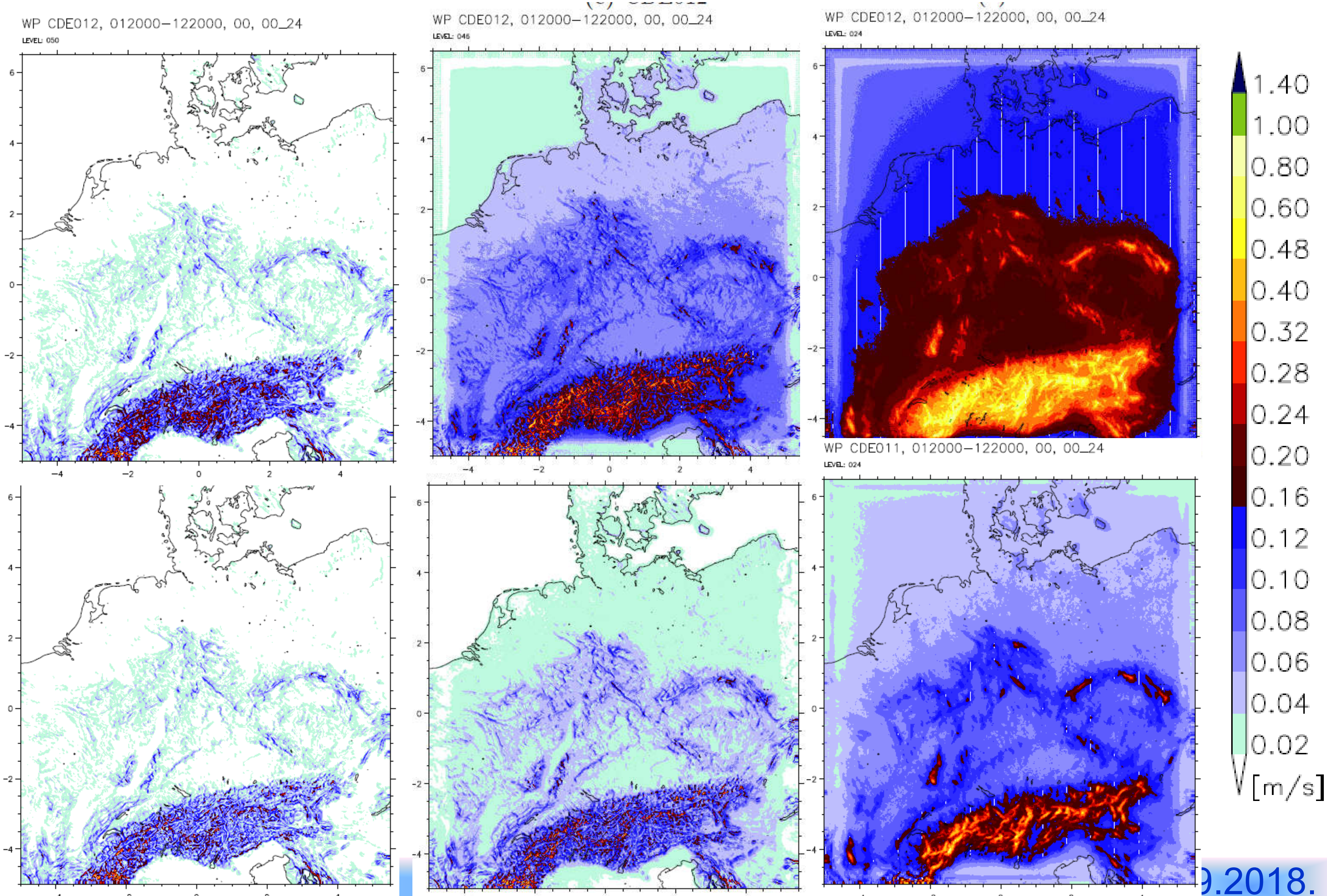
P= 998 hPa | 975 hPa | 500 hPa

CDE012 (symm)

CDE011



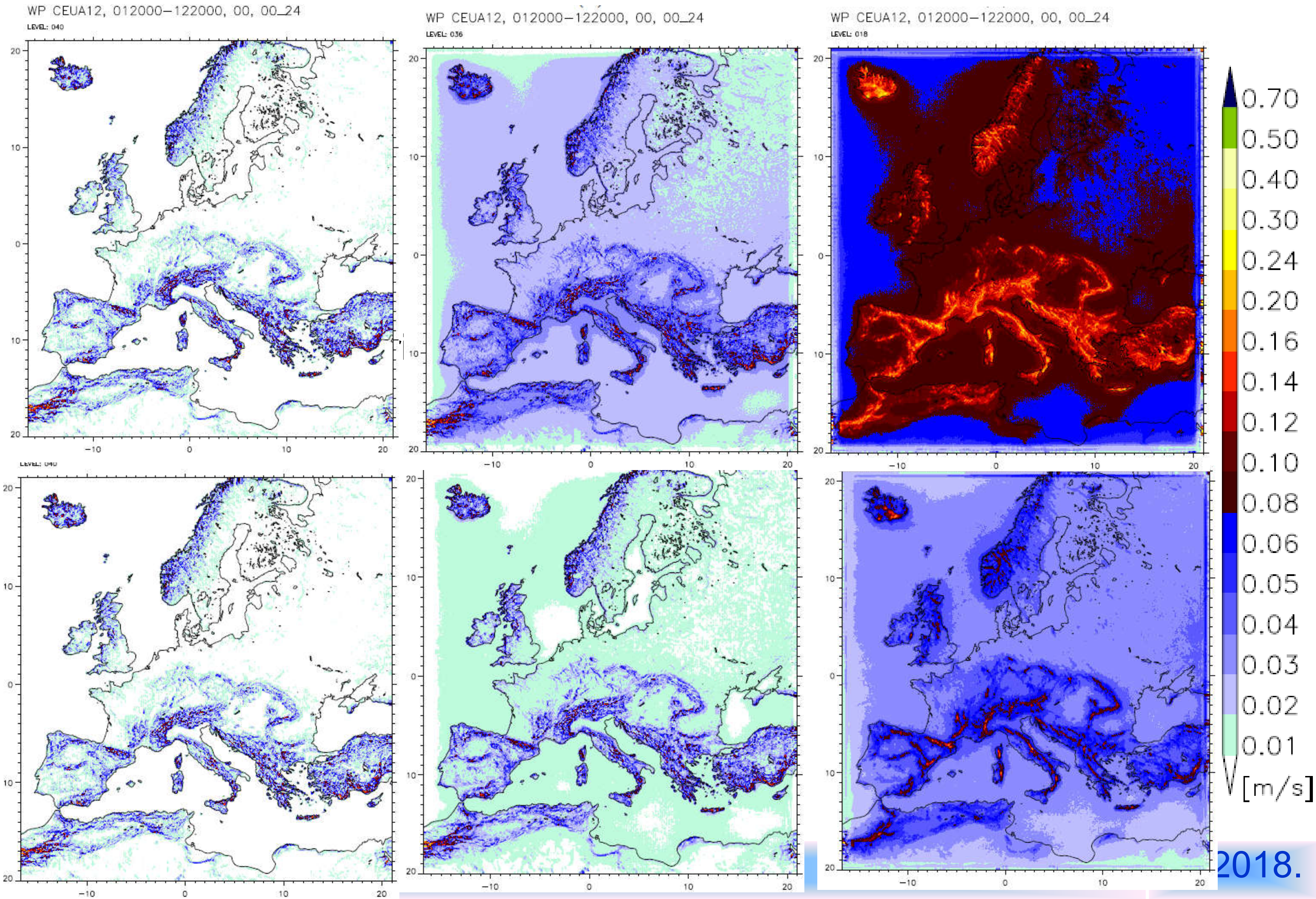
RESULTS for WP = W>0
Mean 2000

Brandenburgische Technische Universität Cottbus

P=	998 hPa	975 hPa	500 hPa

CEU012 (symm)

CEU011



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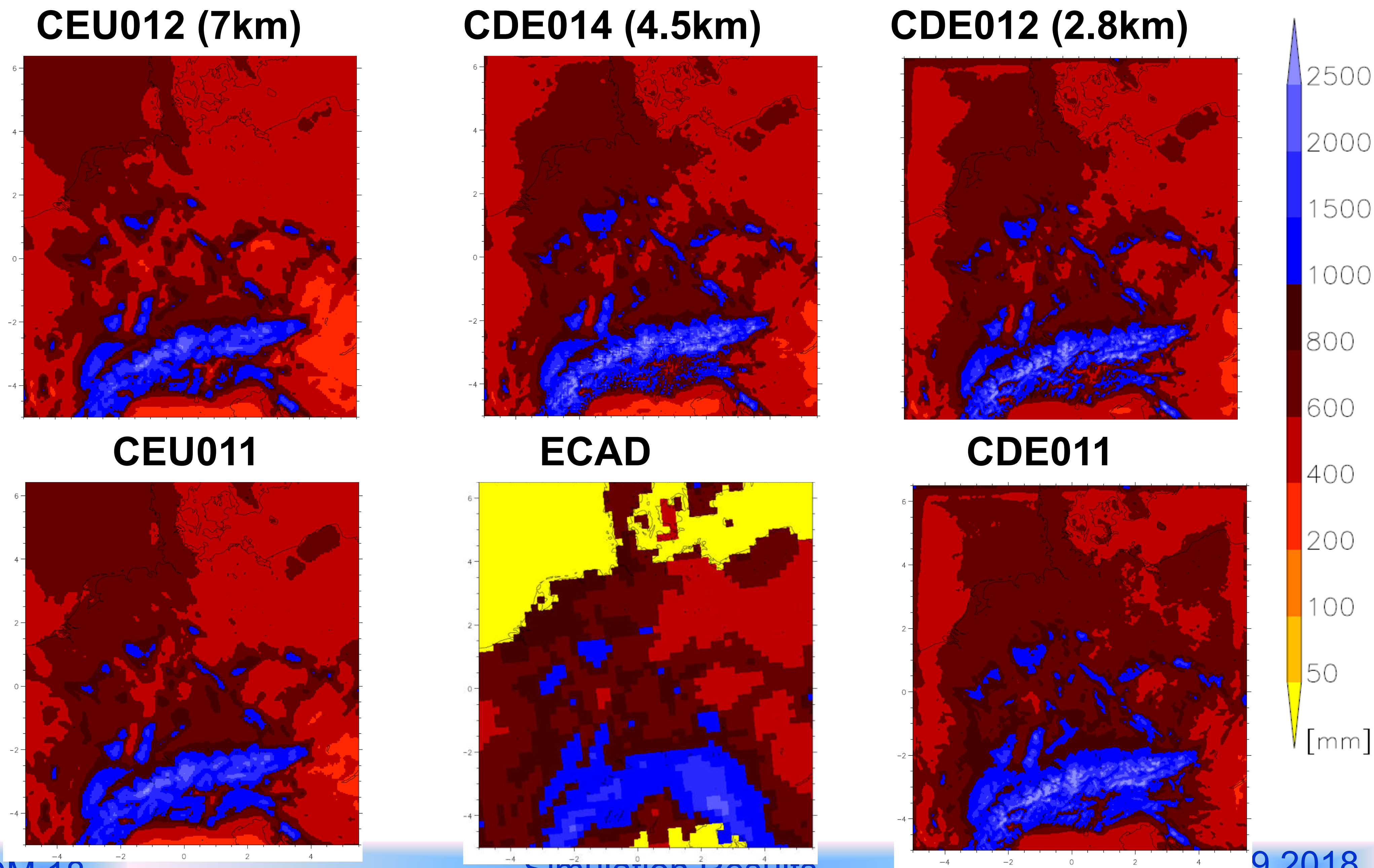
3.1 TOT_PREC mean annual sum 2000-2010



4. RESULTS for TOT_PREC 2000-2014

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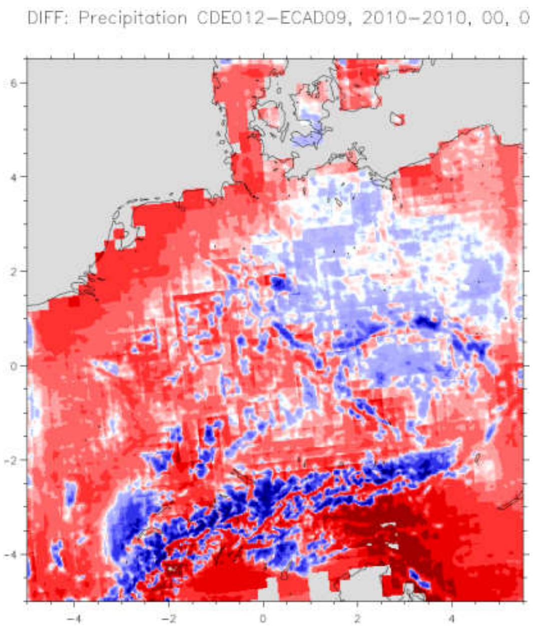
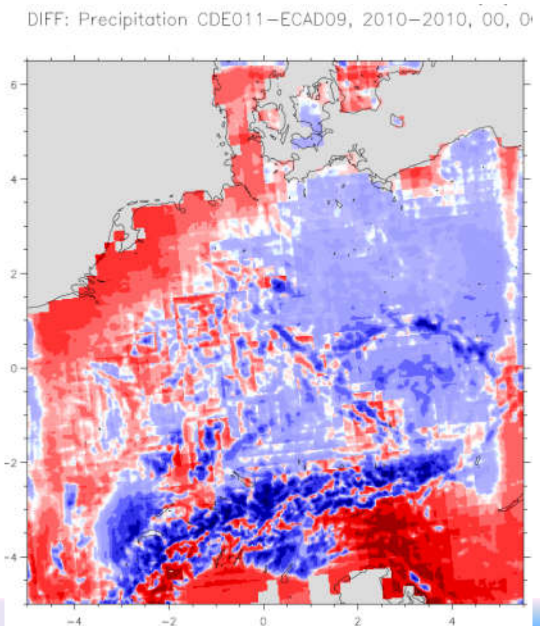
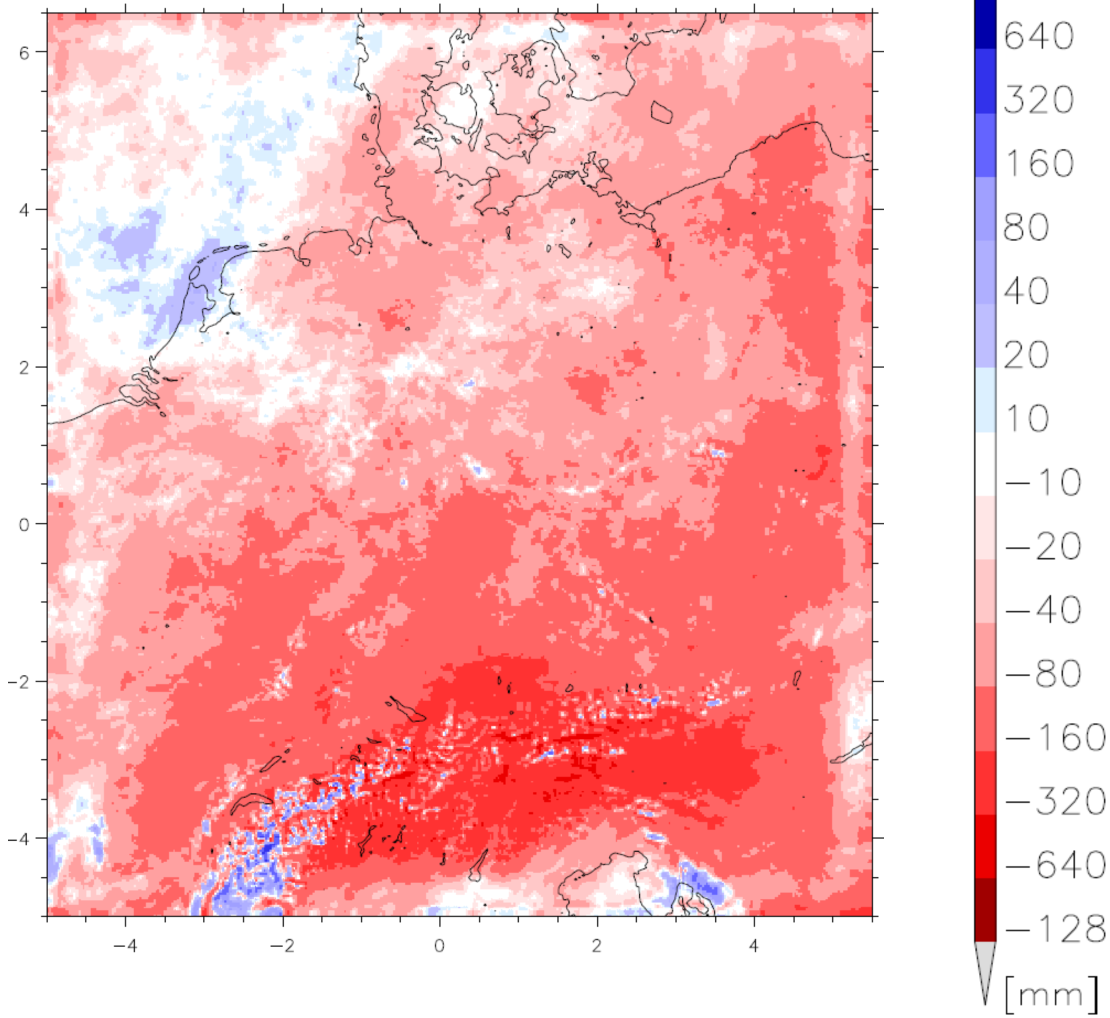
CDE012- ECAD



CDE011- ECAD



CDE012 – CDE011



4. RESULTS for TMIN/TMAX_2M
2000-2014

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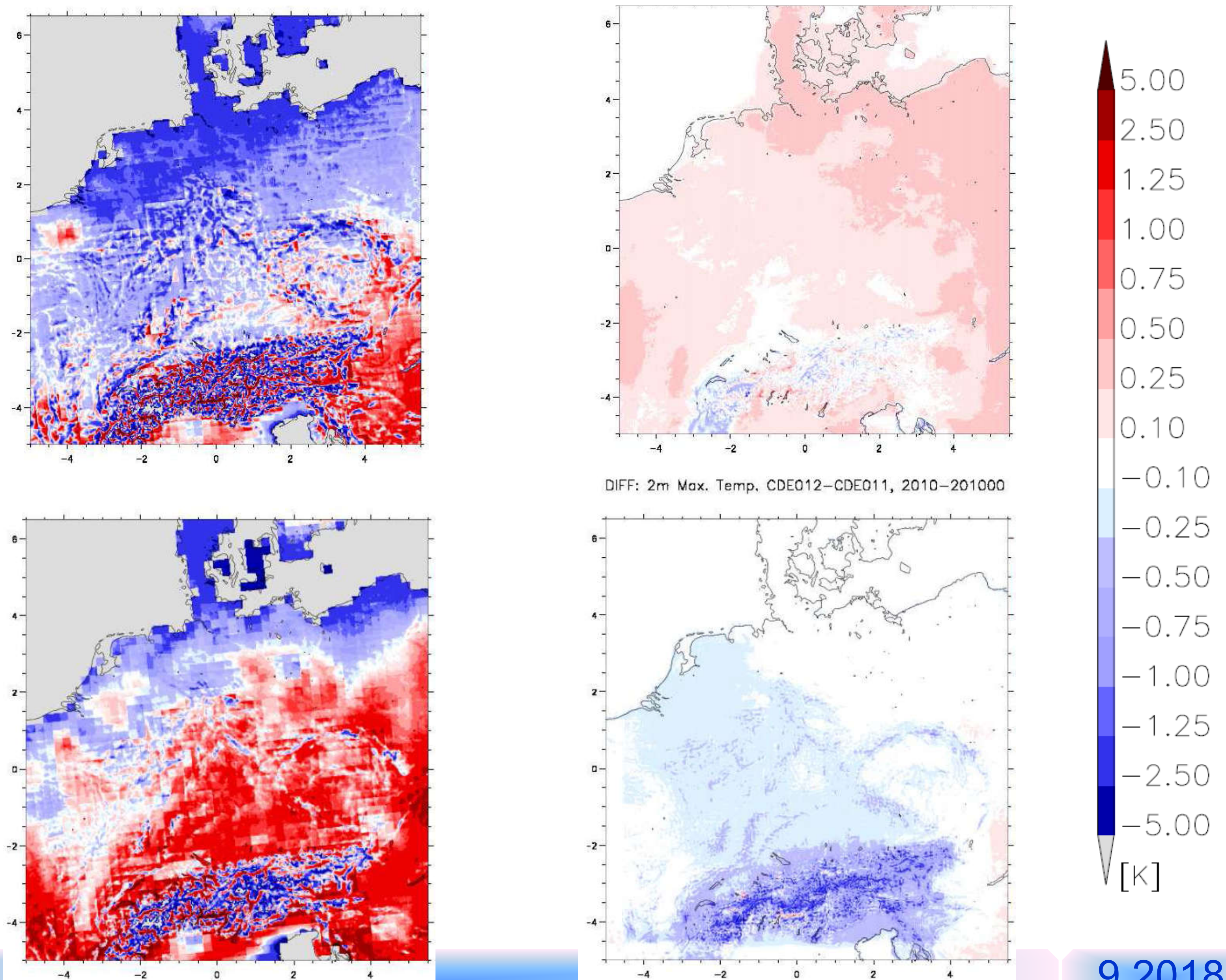
CLM

CDE012 - ECAD | **CDE012 – CDE011**

TMAX_2M

TMIN_2M



COSMO-CLM

3.1 TOT_PREC, 2000-2014

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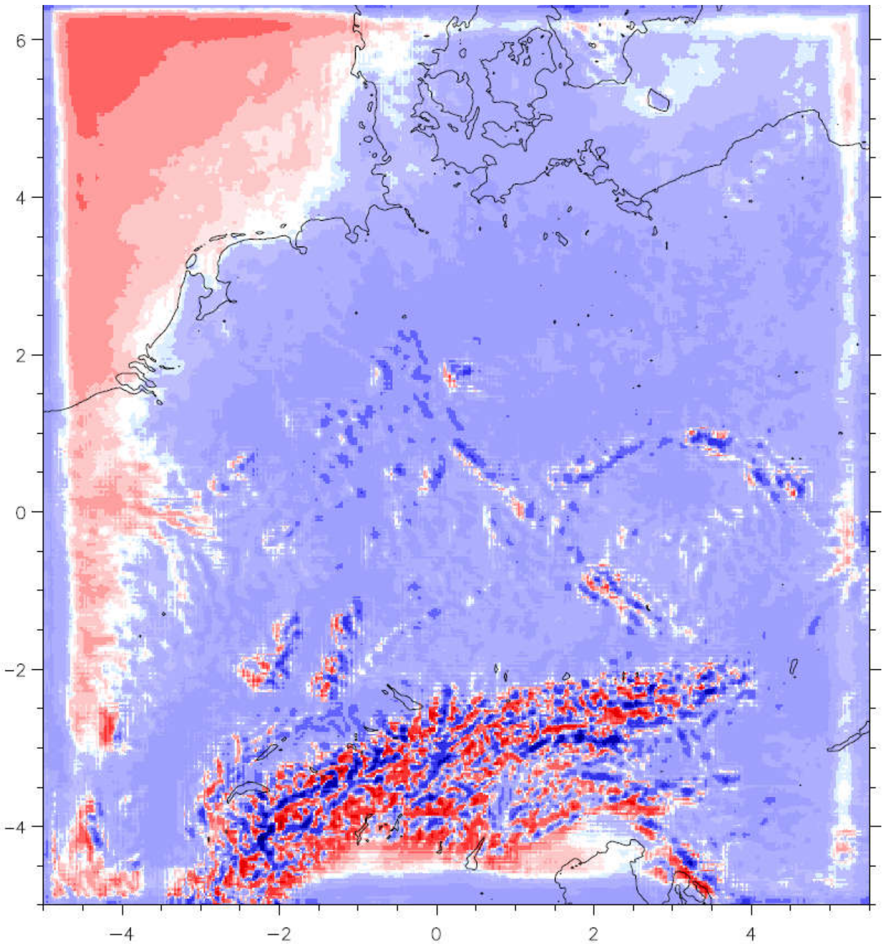
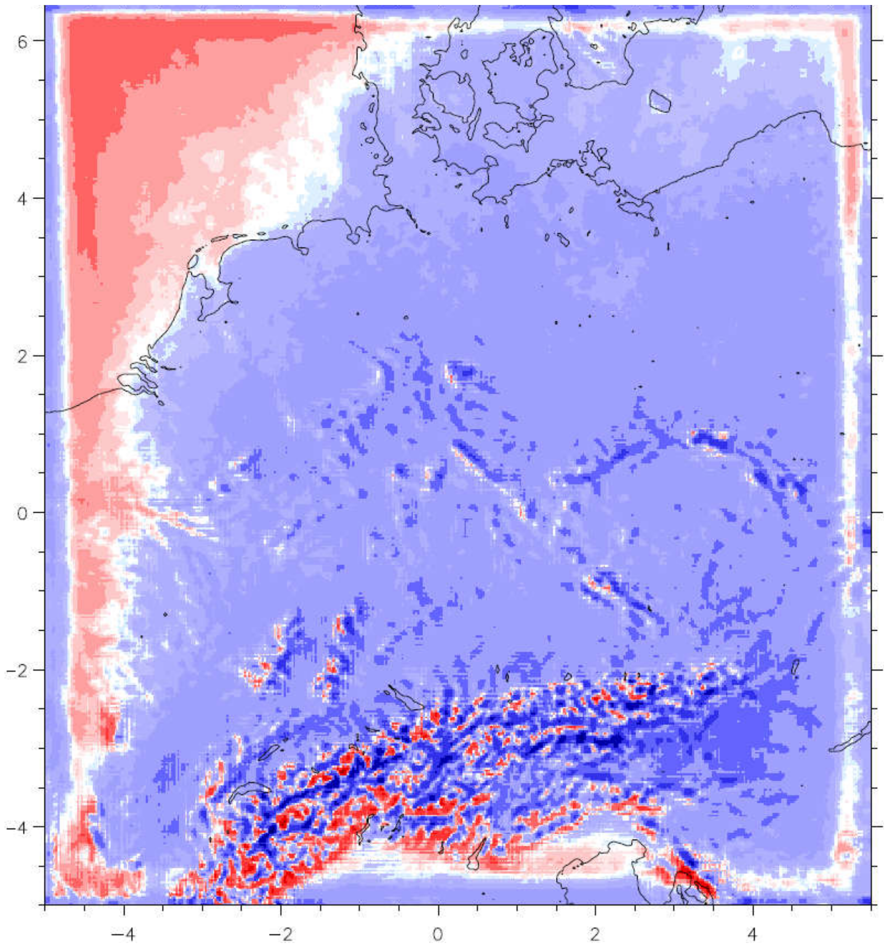
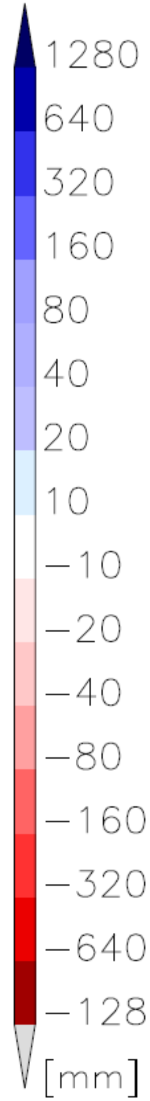
CDE012-CEU012



CDE011-CEU011





Impact of parameterisation (conv.)+ resolution:
CDE012-CEU012: +80 mm/y, D0, S4p4
CDE011-CEU011: +40 mm/y, D0.25, C3p2

3.1 Impact of resolution, numerics and model physics

The symmetric higher order discretization allows to run without artificial diffusion!

← kinetic energy conservation

- **Daily temperature range increased by HOS (1 K)**
- **Vertical updraft velocity approx. doubles with HOS.**
- **Influence to precipitation: it is**
    - **reduced by higher model resolution (factor 2 reduces by 5%)**
    - **increased by Numerical Diffusion**
    - **reduced by deep convection parameterisation by 10 to 20 %**
- **HPBL: no significant differences**

INTERPRETATION:

- Numerical Diffusion is a disturbance of dynamics. This increases the precipitation since the atmosphere has to balance this disturbance

- An Increase of horizontal resolution is reducing the size of the air parcels. Smaller air parcels have higher vertical velocity and thus the system is faster in aequilibrium. This is reducing the precipitation because precipitation occurs if the system is out of aequilibrium.

- Retuning of precipitation is necessary without numerical diffusion.

Final report on PP CELO

Bogdan Rosa, Damian K. Wójcik, Joanna Linkowska and Michał Ziemiański

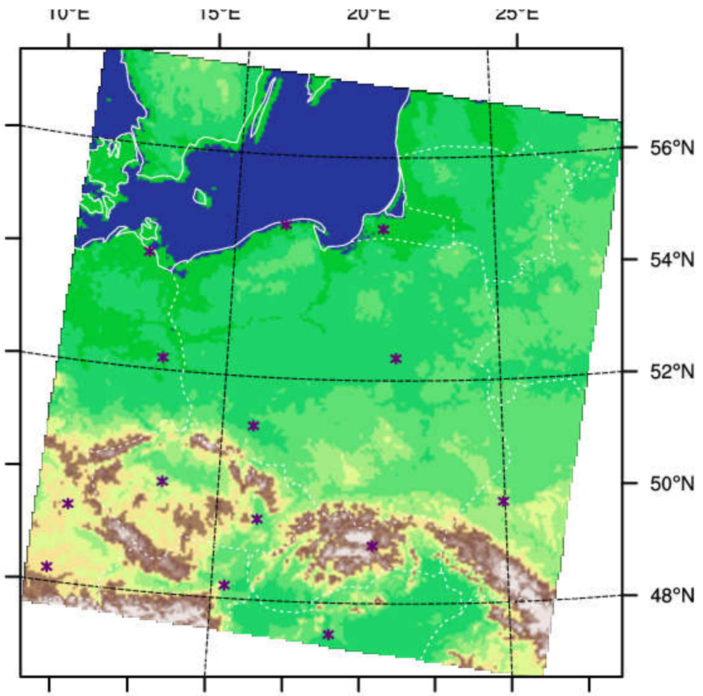
- The **EULAG compressible dynamical core** has been successfully coupled to COSMO 5.04h → it is available for implementation into the **official** COSMO code.
- Optimized integrated code for operational COSMO model with EULAG DC (with no assimilation implemented) has been developed → runs **pre-operationally at IMGW** (Poland) since June 2018
- The compressible dynamical core does not require a special treatment of variable mass in the computational domain nor implementation of time-dependent coordinate.
- Problem with the pressure bias has been solved by applying lateral absorbers.
- Optimization of boundary conditions (velocity bc's for MPDATA) have been performed.
- Implementation of a basic restart subroutine is almost completed.

Verification of pre-operational CELO simulations over Poland

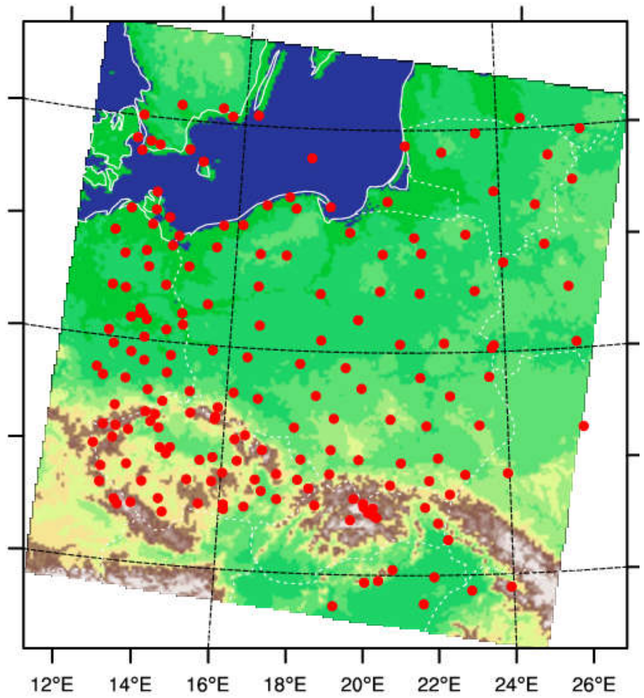
Experiment setup

- COSMO-PL 2.8km domain with 380 x 405 x 50 grid points
- 1-19 August 2018, 0:00 UTC forecasts
- Standard orography filtering is applied
- For CE *dt* = 10 s, for RK *dt* = 25 s
- The set of weather stations used for verification is different from the set of stations utilized for nudging

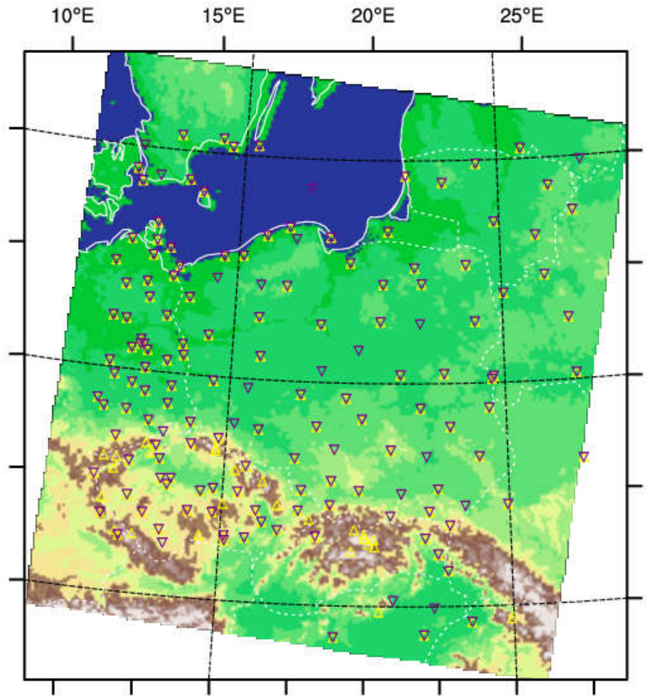
Upper-air sounding stations (14)



SYNOP stations



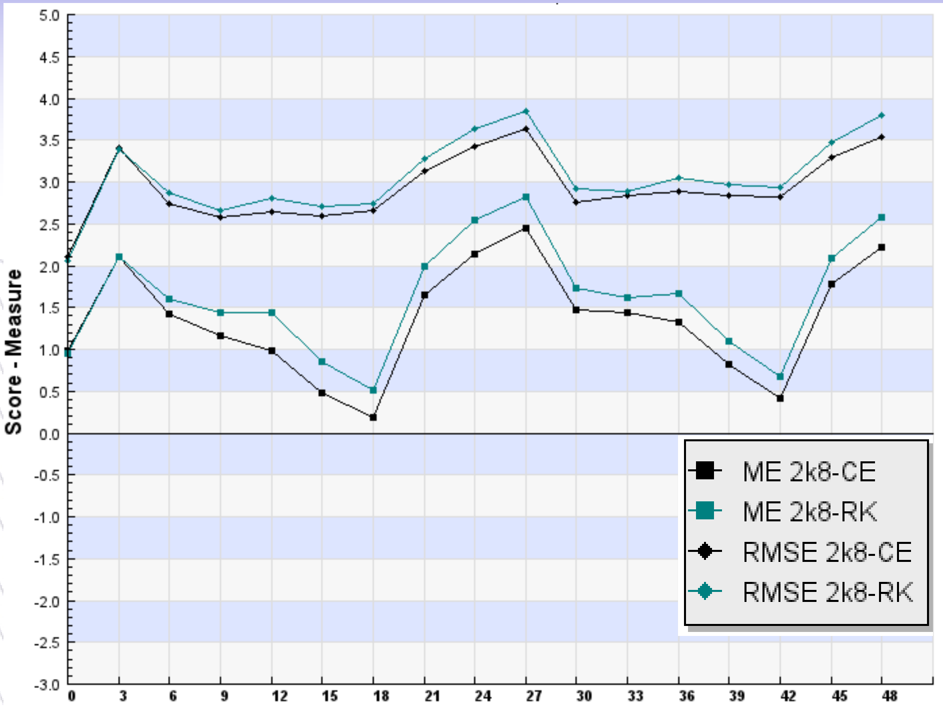
MSLP obs. (violet) and TCC obs. (yellow)



Model setup

- Standard orography filtering is applied
- Turbulence (***itype_turb=3***), microphysics (with cloud ice), soil model and radiation (with coefs. updated every 7.5 minutes) are turned on
- For COSMO Runge-Kutta ***irunge_kutta=1*** and ***itype_fast_waves=2***
- For COSMO Runge-Kutta the numerical filtering is turned on
- The set of weather station used for verification is different from the set of stations utilized for nudging
- For CI *dt* = 10 s, for RK *dt* = 20 s

Mean Sea Level Pressure and Temperature at 2m



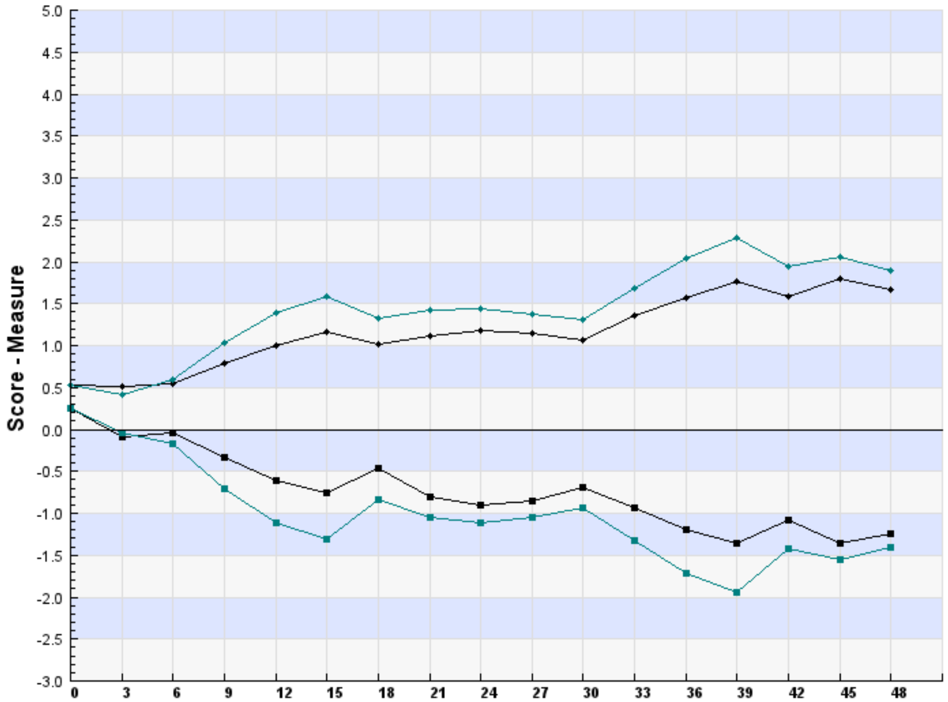
Temperature at 2m

1. The CE 5.04h model slightly outperforms RK 5.04h

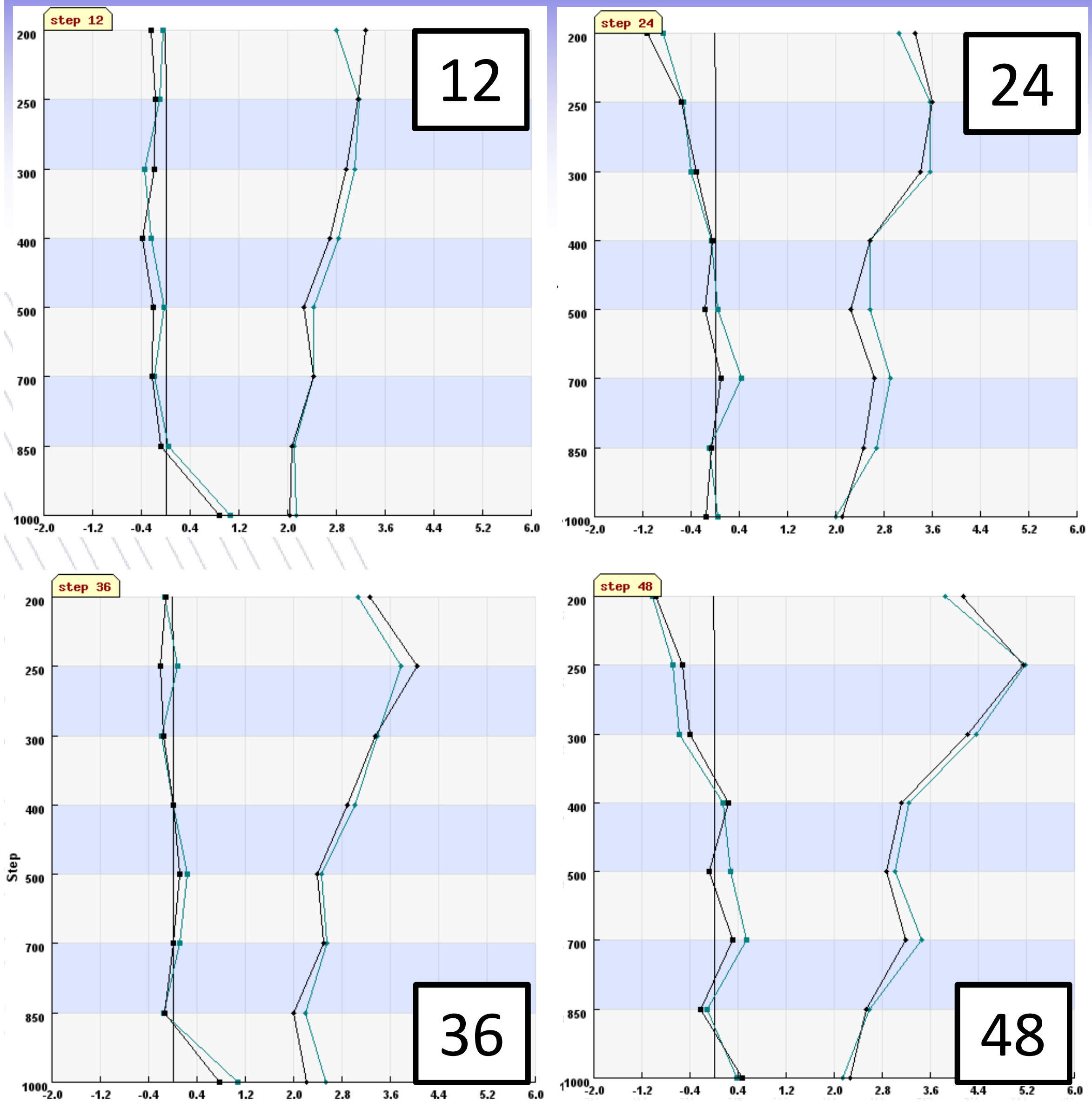
2. The daily cycle is clearly visible in simulations results of both models.

MSLP

The CE 5.04h outperforms RK 5.04h



Wind speed (upper air)

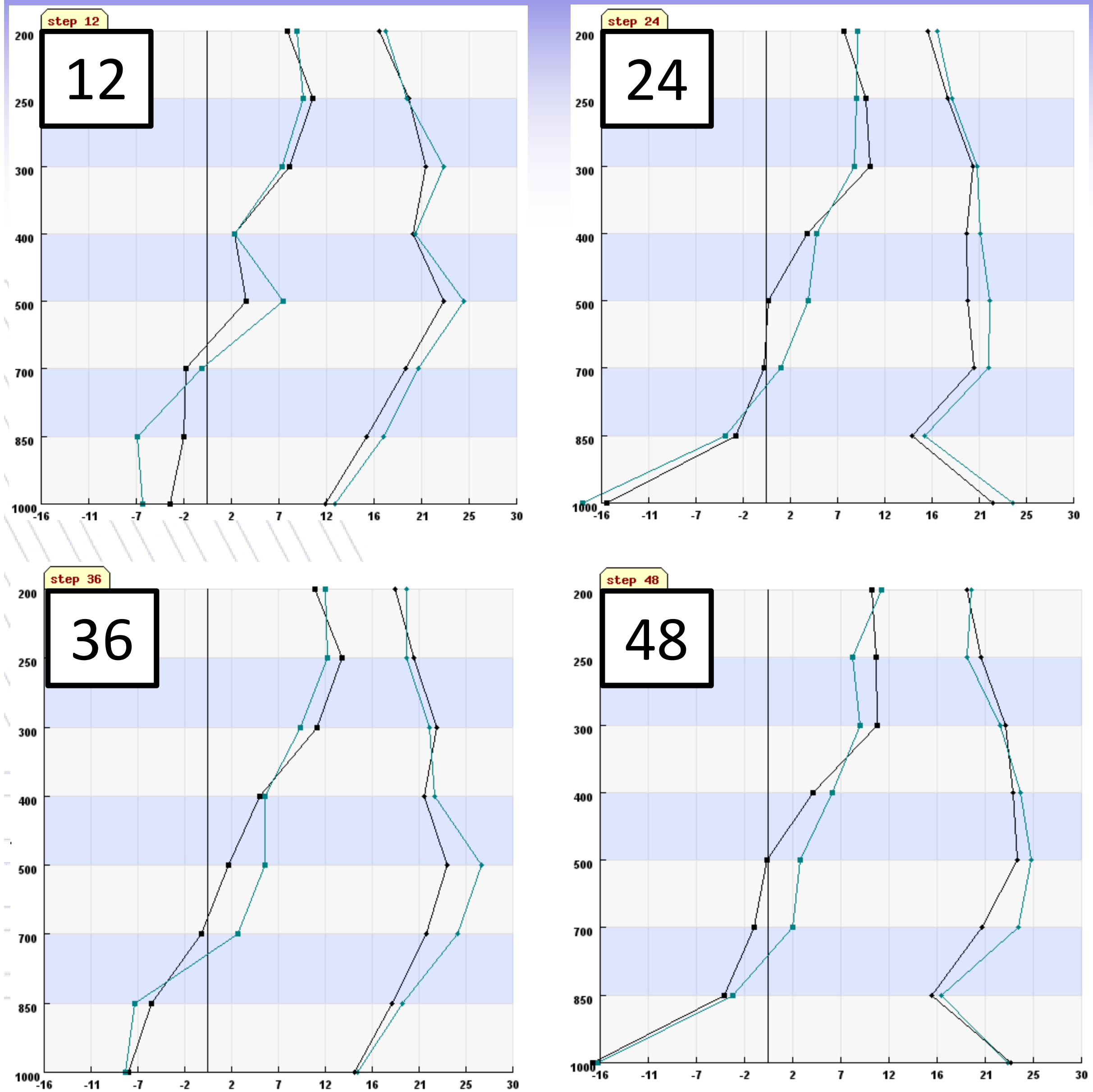


1. Between 1000 and 700 hPa forecasts computed using CI 5.04h are more accurate

2. Between 500 and 300 hPa the scores are similar for both models

3. Above 200 hPa, RK forecast is closer to observations

Relative humidity (upper-air)



1. For most time instants RMSE of CE scores is lower than RMSE of RK (except 300-250 hPa at 36 and 48 hour)

2. Significantly lower Bias is observed in CE results between 1000 and 500 hPa

3. On the other hand, between 300 and 250 hPa Bias is lower in RK simulations.

Conclusions

- **The EULAG model has been successfully coupled to the COSMO framework ver. 5.04h and can be used for operational weather forecasting, with nudging as the assimilation scheme → runs pre-operational at IMGW since June 2018**
- Number of simulations have been performed both with default settings and parameters optimized within the CALMO project.
- Operational tests of COSMO-EULAG over COSMO-PL 2.8km domain show that these forecasts are competitive when compared to the forecasts obtained with the default COSMO model.

Thank you for your attention!