Development and operationalization of compressible COSMO-EULAG for regional numerical weather prediction

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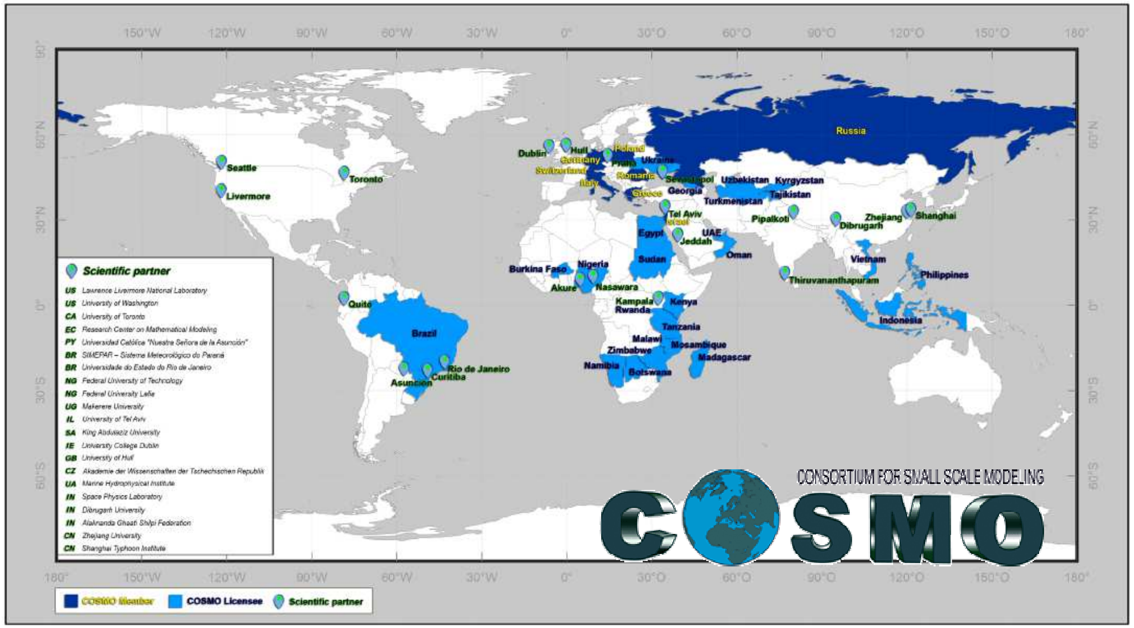
Outline

1. Short history of the CELO Priority Project
2. Solution of the pressure forecast problem
3. Verification scores for compressible COSMO-EULAG
4. Realistic flow over the Alps in high-resolution simulations
5. Plans and Summary

COSMO Consortium

- The **Co**nsortium for **S**mall-scale **Mo**deling (**COSMO**) develops and maintains a non-hydrostatic compressible limited-area atmospheric model for operational and research applications
- Polish weather service IMGW-PIB is a member of the COSMO consortium
- Since 2002 IMGW-PIB employs the COSMO model for weather forecasting
- Since 2002 a significant decrease of horizontal model grid size in operational runs was implemented, from 14km down to 2.8 km, allowing to improve the quality of operational forecasts

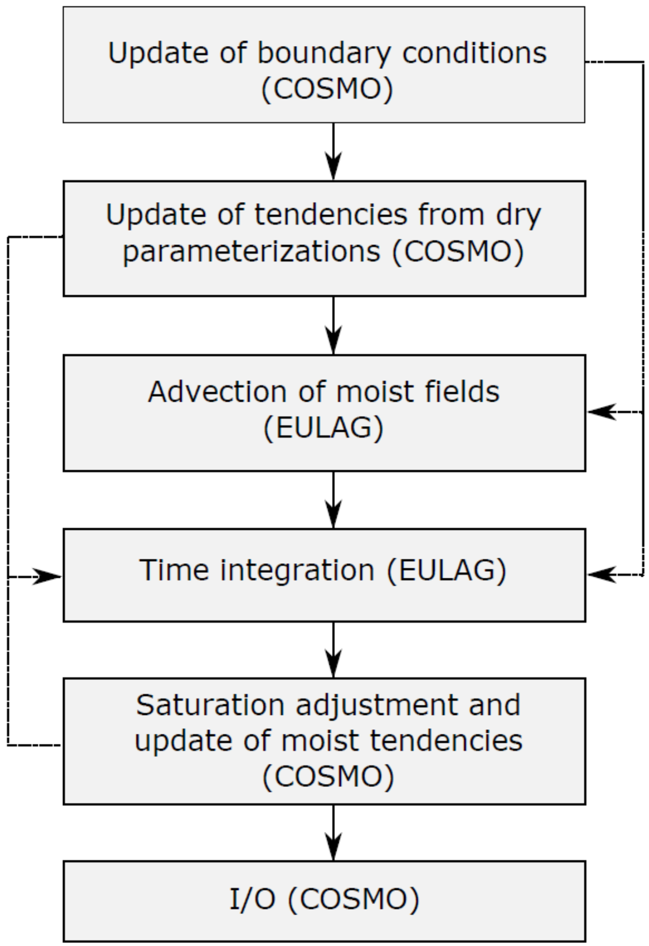


Map of the COSMO members and licensees
as well as scientific partners (only for non-COSMO member countries) in 2017.

PP Conservative Dynamical Core: COSMO-EULAG (anelastic)

Between 2009 and 2014 our research at IMGW-PIB was focused on coupling the COSMO model with nonhydrostatic anelastic EULAG solver for geophysical flows

This research resulted in a prototype anelastic COSMO-EULAG model (CE-A) that is capable to provide weather forecasts for limited-area computational domains (pressure forecast from the driving model; no data assimilation).



Positive outcome from the CDC PP resulted in inclusion of CE-A model in the COSMO Science Plan 2014-2020 and paved a way for the new project aiming at the CE-A model operationalization.

The main publication summarizing our numerical model development effort:

„Convection-permitting regional weather modeling with COSMO-EULAG: Compressible and anelastic solutions for a typical westerly flow over the Alps"
Kurowski et. al., Monthly Weather Review, 2015.

PP COSMO-EULAG Operationalization: compressible core

Problems inherited from CDC PP:

1. Full pressure forecast
2. Applicability of the anelastic approximation (sub-synoptic scales)

Proposed solutions (PP CELO):

1. Extend anelastic model with capability to handle time-varying total mass (abandoned in 2014)
2. Incorporate the new EULAG compressible core developed by Piotr Smolarkiewicz and colleagues [1,2]

Realization of PP CELO:

1. Idealized tests of CE-C model successful
2. Competitive realistic forecasts, including pressure forecast
3. Preparation of the final code and operational runs (ongoing)
4. HPC-related issues shifted to the project of Zbigniew Piotrowski (PROPOZE - externally-founded)

[1] Smolarkiewicz, P. K., C. Kühnlein, and N. Wedi 2014 *J. Comput. Phys.* vol. 263 p. 185-205
[2] Kurowski, M. J., W. W. Grabowski, and P. K. Smolarkiewicz 2014 *J. Atmos. Sci.* vol. 71 p. 3767–3787

Today's model setup

- Compressible implicit EULAG dynamical core (anelastic one available as well) developed by P. Smolarkiewicz et. al.
- Communication between EULAG and COSMO is based on infrastructure developed for anelastic core (project CDC)
- Outcomes of COSMO parameterizations (forcings) are forwarded to the dynamical core
- Moist fields are advected with MPDATA A
- Lateral pressure absorbers allow to obtain realistic pressure forecasts
- Removal of additional level at the surface: the first EULAG level coincides with the first COSMO mass level at 10 m above the ground
- I/O and restart is entirely handled by the COSMO framework
- Recently coupled with the very new COSMO 5.04h (implementation is still under testing)

Solution of the pressure forecast problem

Pressure drift

1. We observed a systematic drift of pressure with surface amplitude up to few hPa during a day
2. That suggested that the bc's, themselves, do not provide sufficiently accurate mass flux into the computational domain
3. The similar problem is observed also in COSMO RK dynamical core which additionally uses lateral pressure absorbers to alleviate the problem
4. Application of lateral pressure absorbers solves the problem also for COSMO-EULAG

Application of the absorber for semi-realistic simulations

Semi-realistic simulations using COSMO Runge-Kutta (RK) and compressible COSMO-EULAG (CE) were performed to diagnose the pressure bias development as well.

Computational domain:

- Bay of Biscay (flat)
- Realistic b.c.
- $\Delta X = 2.2$ km, $\Delta t = 15$ s

Test case:

- 15 November 2013 (Azoren High)

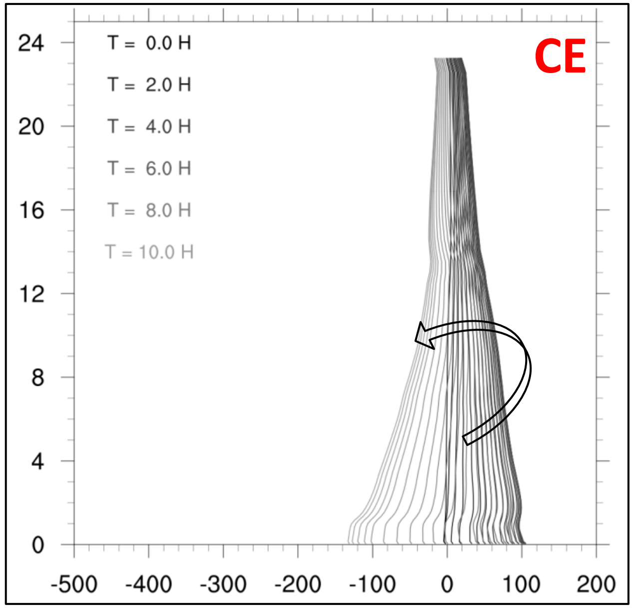
Configuration:

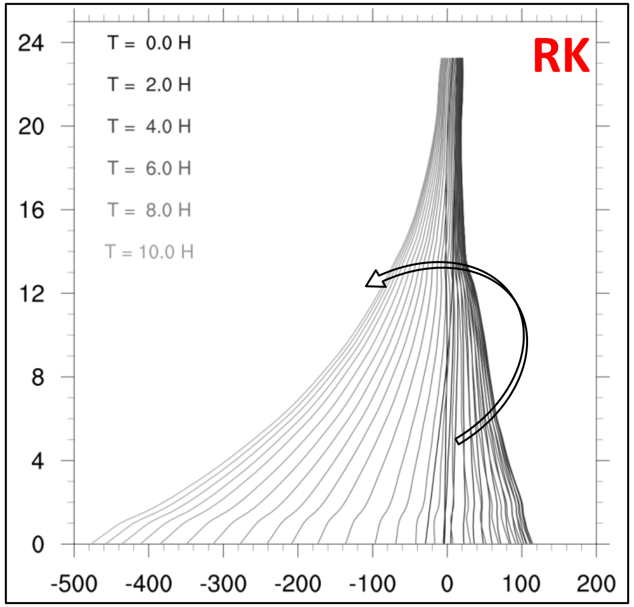
- Turbulence parameterization is turned on
- Moist microphysics and saturation adjustment are turned off
- Soil (sea) processes are turned off
- Water vapor enters buoyancy and there are no sources / sinks of water vapor

Figures in following slide show time evolution of horizontally averaged pressure perturbations. The perturbations are calculated with respect to the time-evolving pressure from the driving COSMO-7 simulation.

Results

Semi-realistic simulations: **results without absorber for pressure**

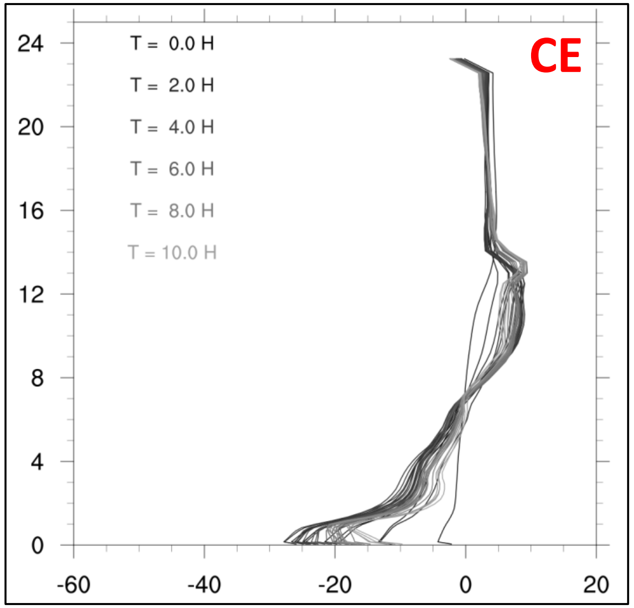


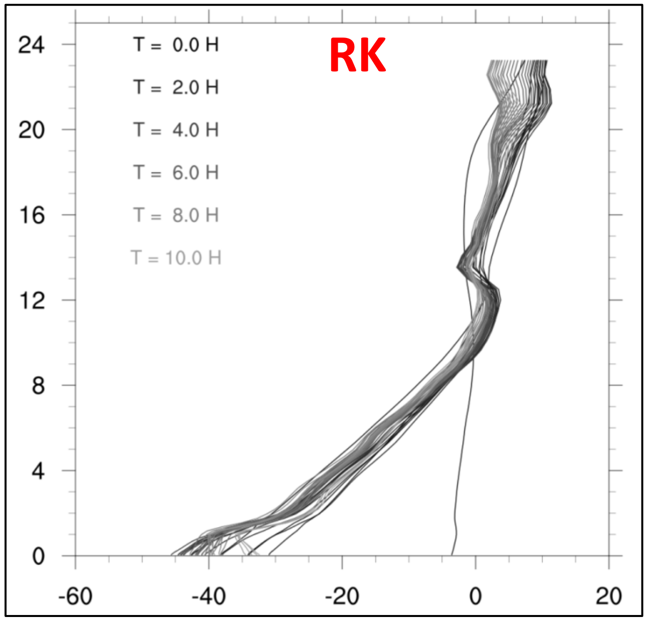


Pa

Disabling the pressure absorber in RK results in the development of a pressure bias similar to that observed in CE results.

Semi-realistic simulations: **results with absorber for pressure**





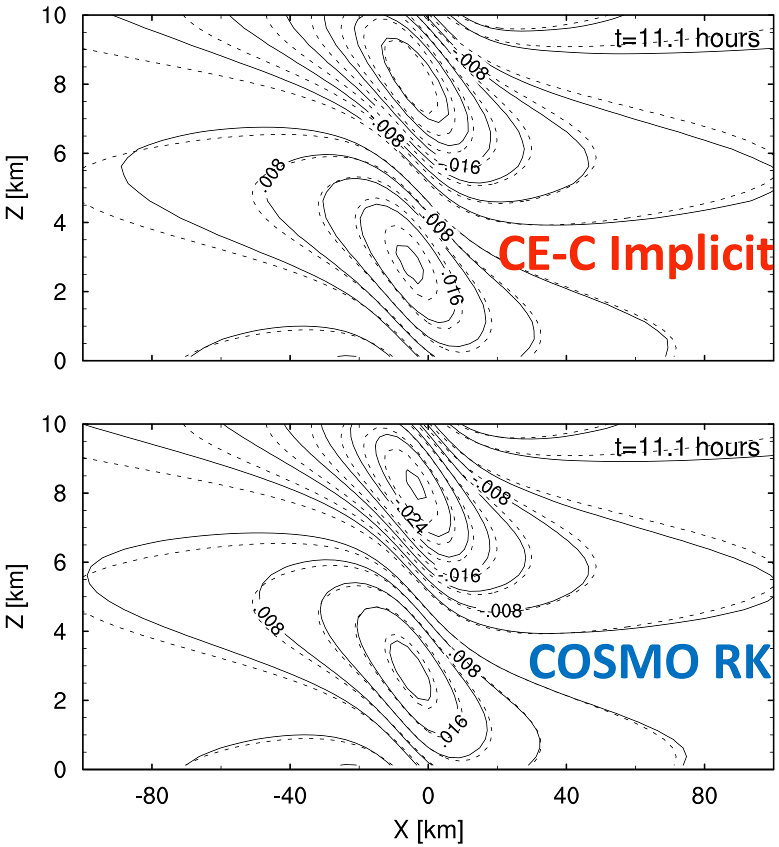
Pa

Pressure bias is tremendously reduced in simulations with pressure absorber

Linear hydrostatic flow over a hill:

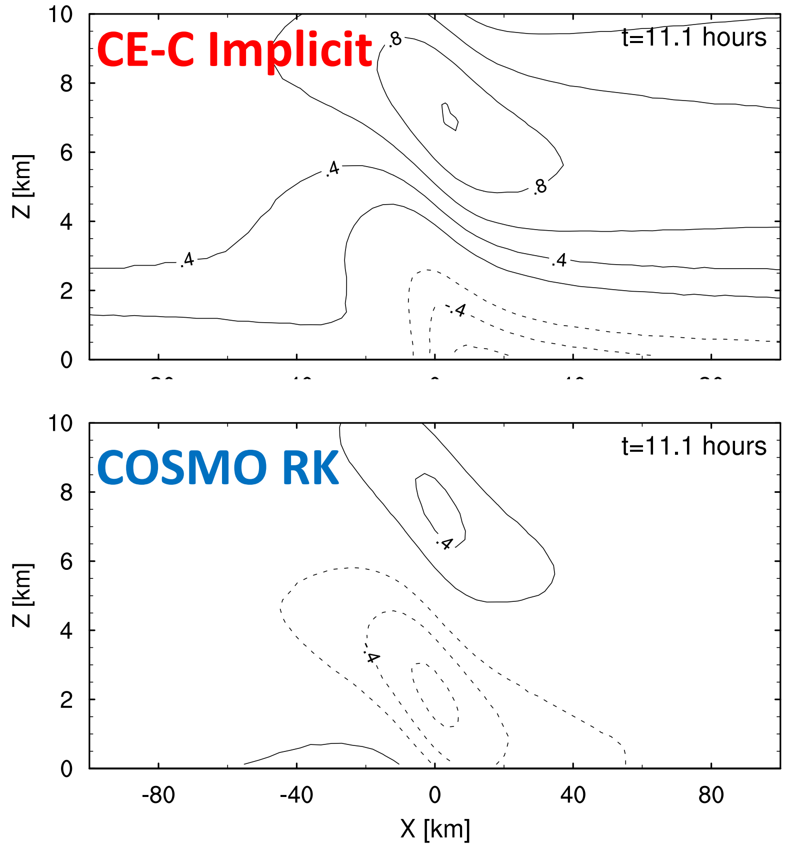
- Δx = 3km, Δz = 250 m
- h_0 = 1m, a = 16km
- U = 32 m/s
- N = 0.0187 s^{-1}

U-wind component perturbation:



Models solutions for the wind are consistent with the analytical formula from Klemp et. al.(1977; dashed lines).

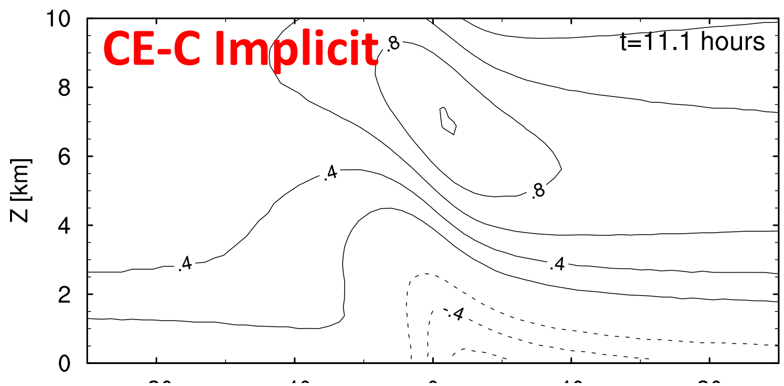
Pressure perturbation

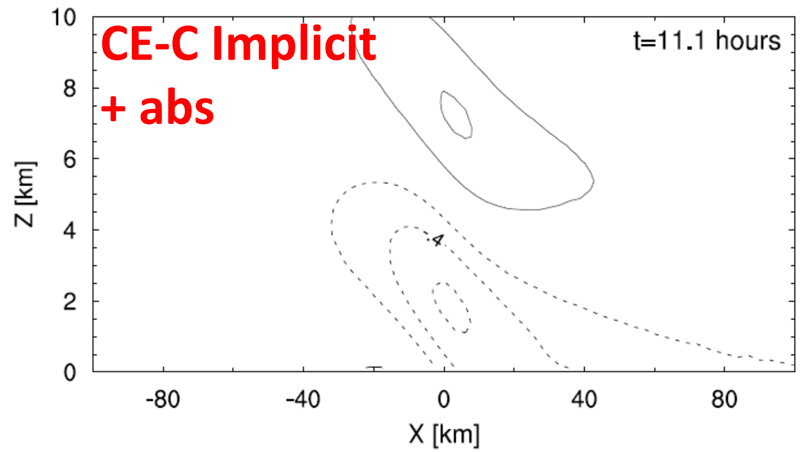


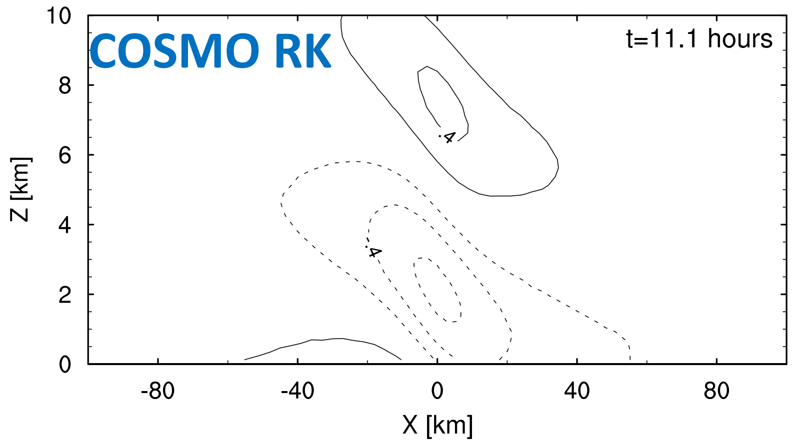
- Positive „pressure bias" observed across the troposphere and stratosphere for CE-C

	P'$_{min}$ [Pa]	P'$_{max}$ [Pa]
COSMO RK	-0.66	**0.44**
CE-C Impl.	-0.65	**1.00**

Application of lateral pressure absorbers for COSMO-EULAG





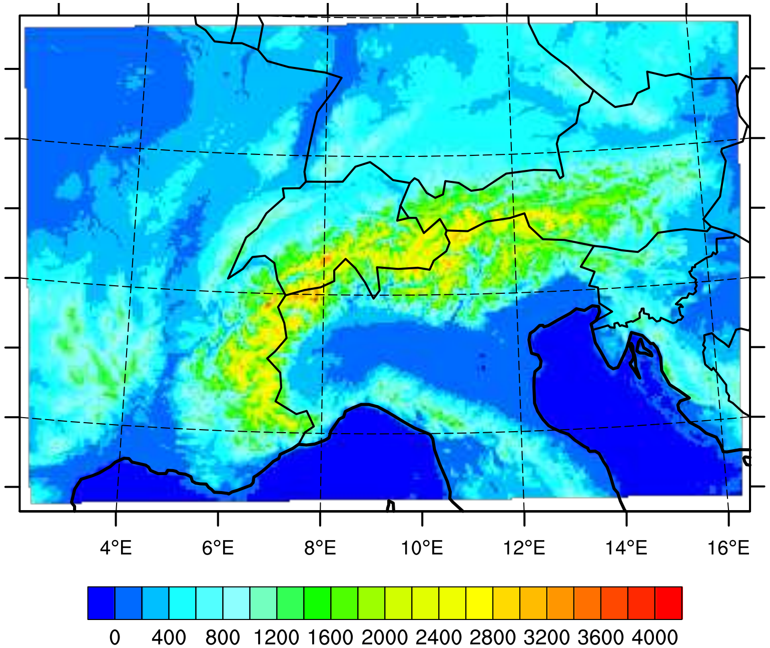


	P'_{min} [Pa]	P'_{max} [Pa]
COSMO RK	-0.66	0.44
CE-C Impl.	-0.65	1.00
CE-C Impl. + abs.	**-0.63**	**0.42**

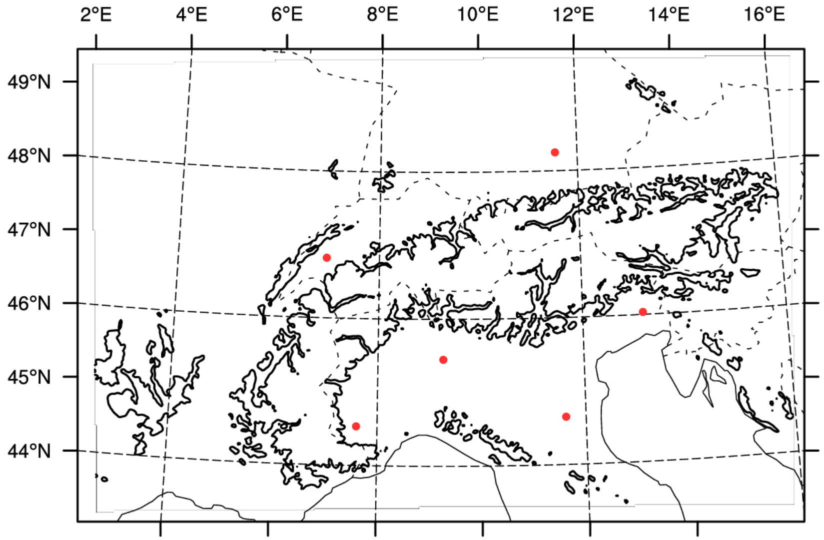
Verification scores for compressible COSMO-EUALG

Verification Scores for CE-C model

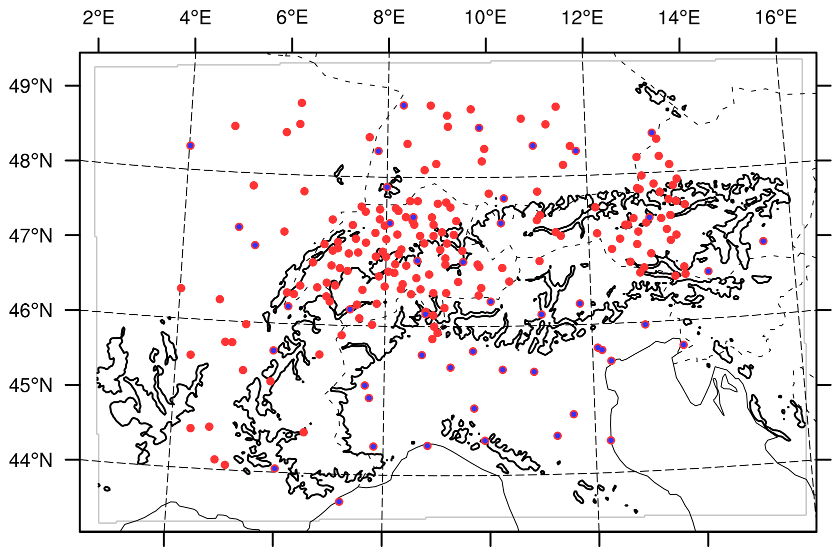
- COSMO 5.04h framework: C-RK and CE-C models
- Forecasts from 0 to +48 UTC
- Each model utilizes the same boundary conditions
- Δ X = 2.2 km, 60 levels in vertical up to 24 km AMSL
- 1-30 June 2013
- 1-15 November 2013



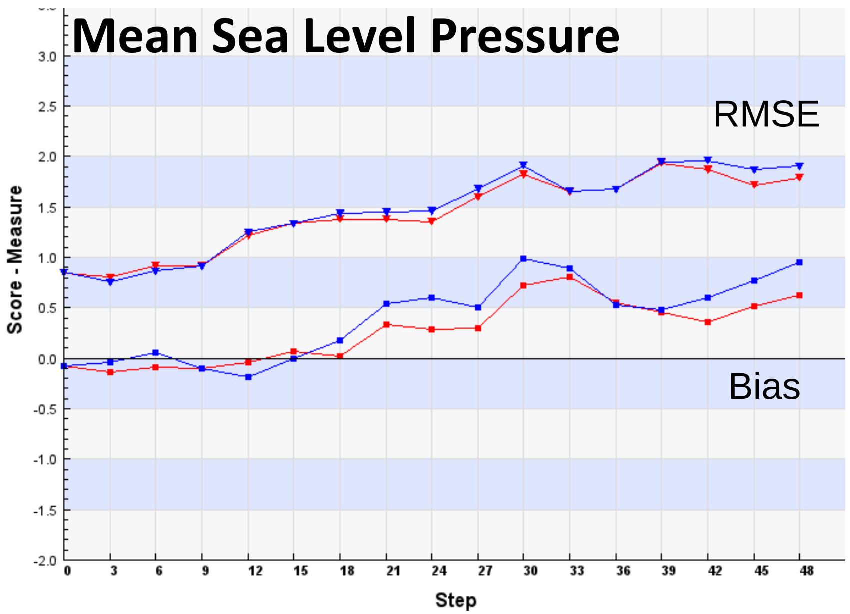
TEMP verification: 6 stations

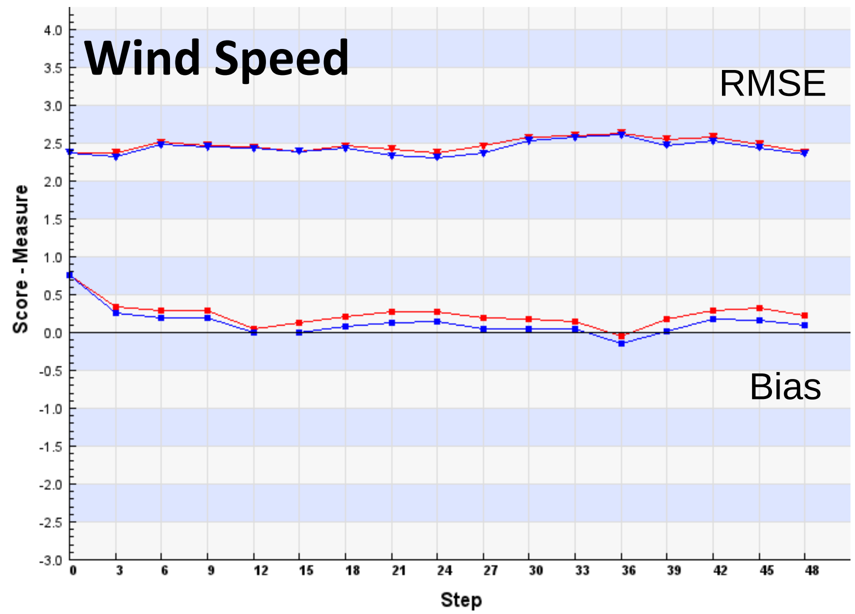


SYNOP verification: 217 stations



Surface scores for November 2013





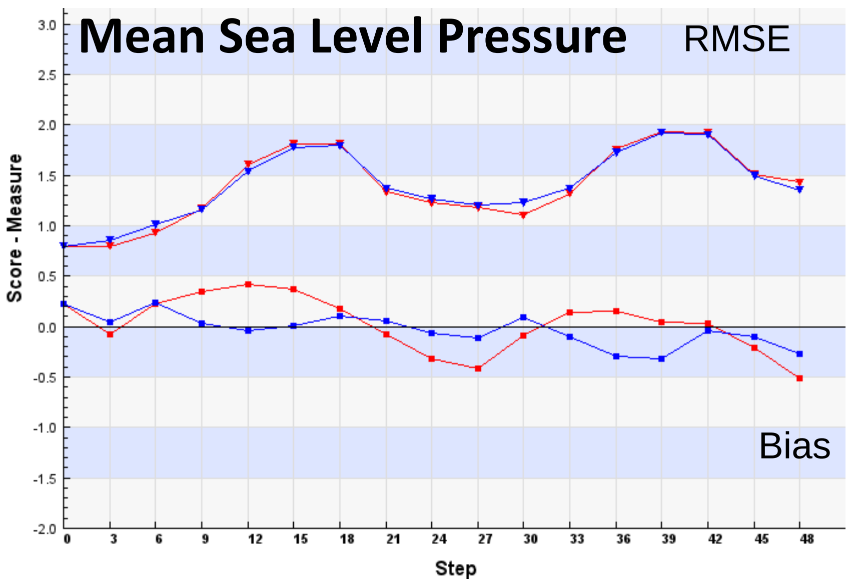
- Magnitude of RMSE is very similar for CE-C and C-RK.
- In this case time-evolution of the Bias is similar for both models
- During the second day Bias of CE-C tends to be smaller

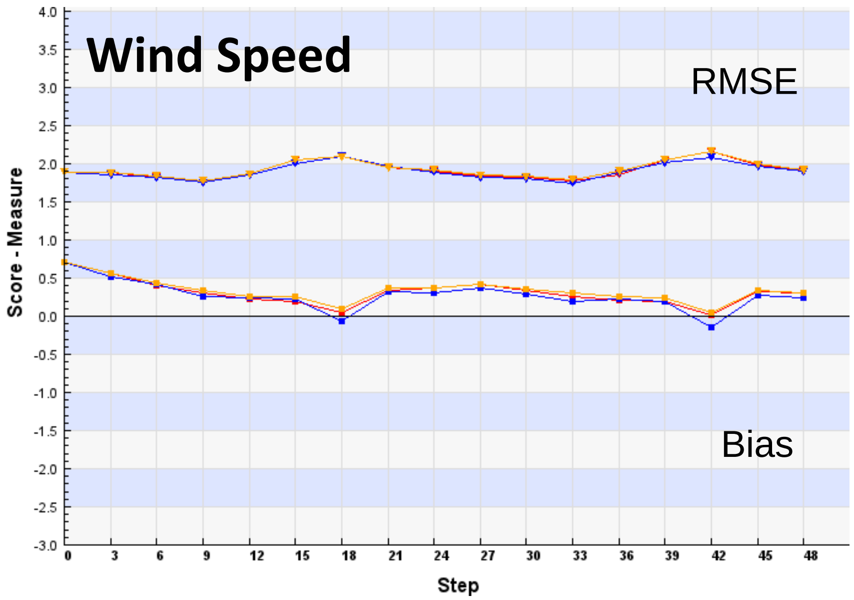
- The Bias of CE-C is systematically higher.
- The differences in RMSE are small

November verification covers :

1. COSMO model with R-K core
2. COSMO-EULAG 5.04 h model with compressible core (CE-CI)

Surface scores for June 2013





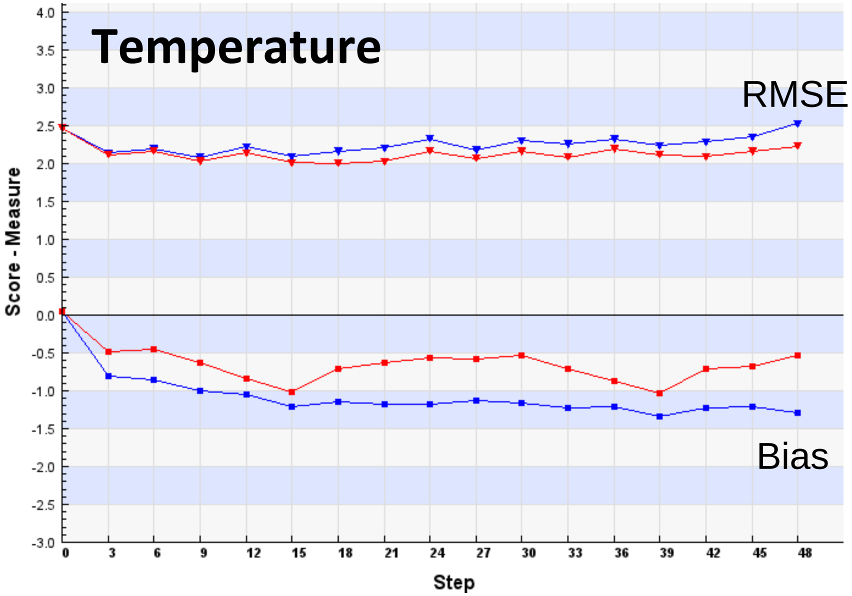
- RMSE comparable for CE-C and C-RK
- Bias for CE-C is higher during the first forecast day and night

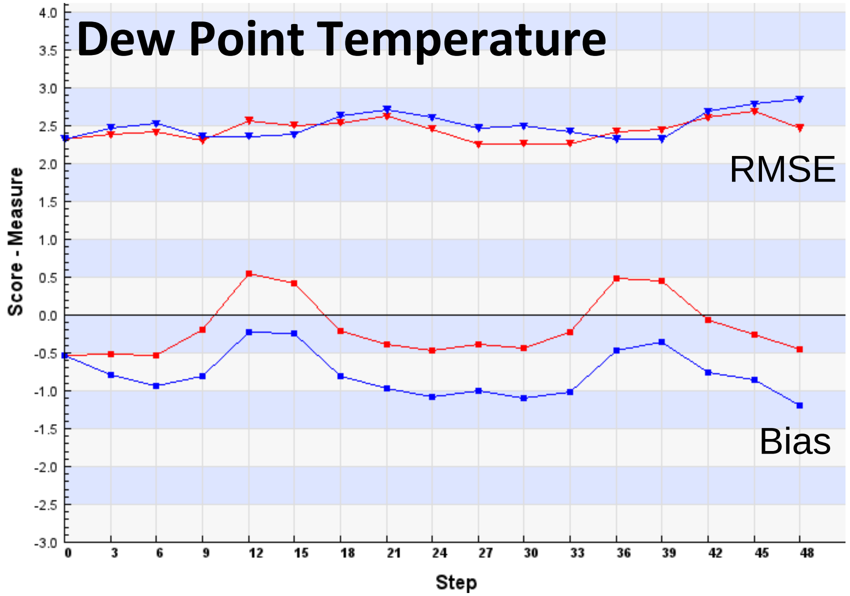
- Comparable scores of ME and RMSE with bias tending to be slightly higher for CE

June verification covers :

1. COSMO model with R-K core
2. COSMO-EULAG 5.04 h model with compressible core (CE-CI)
3. COSMO-EULAG 5.04h model with anelastic core (CE-A)

Surface scores for November 2013



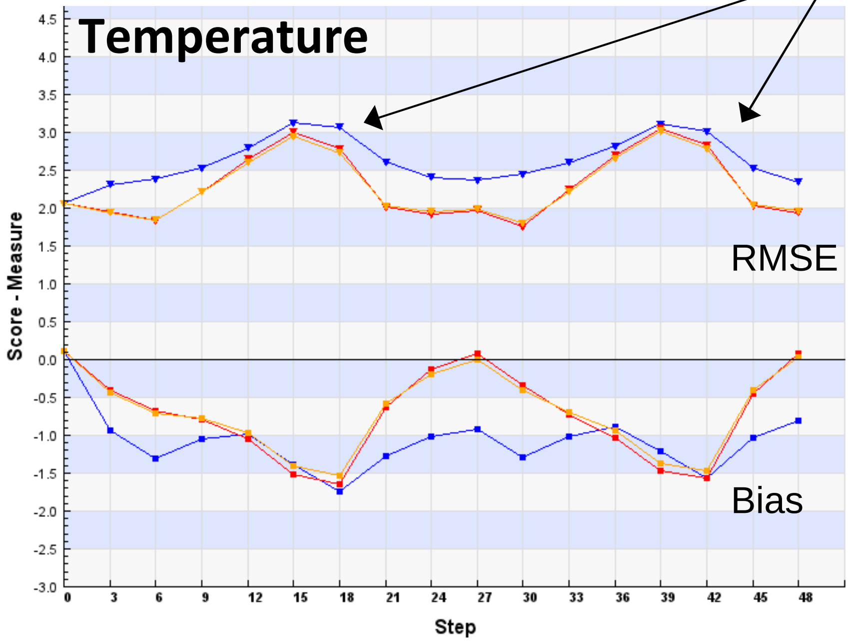


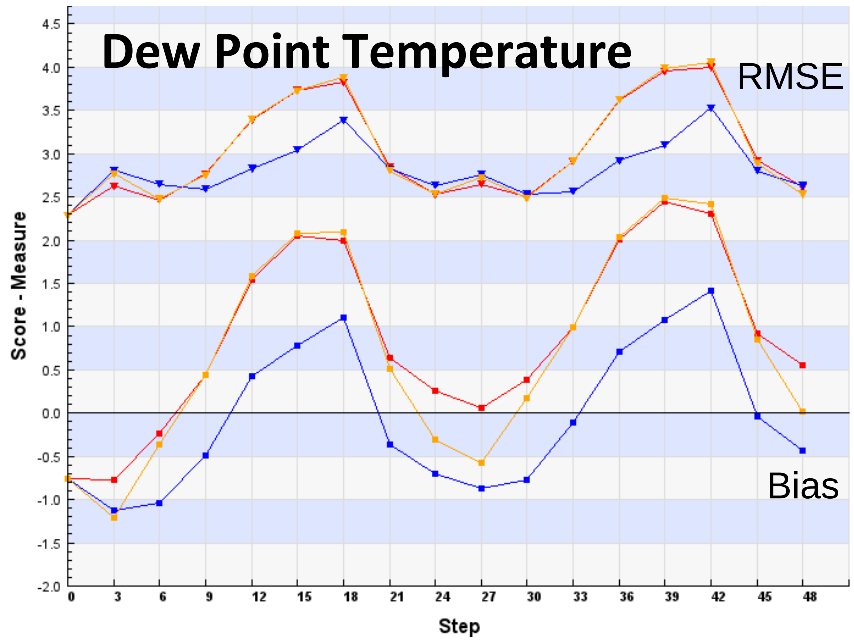
- Scores of CE-C model are better especially for Bias

- CE-C Bias is generally much smaller than C-RK one
- RMSE are comparable with C-RK (but slightly lower at afternoons)

Surface scores for June 2013

Diurnal cycle in error magnitude

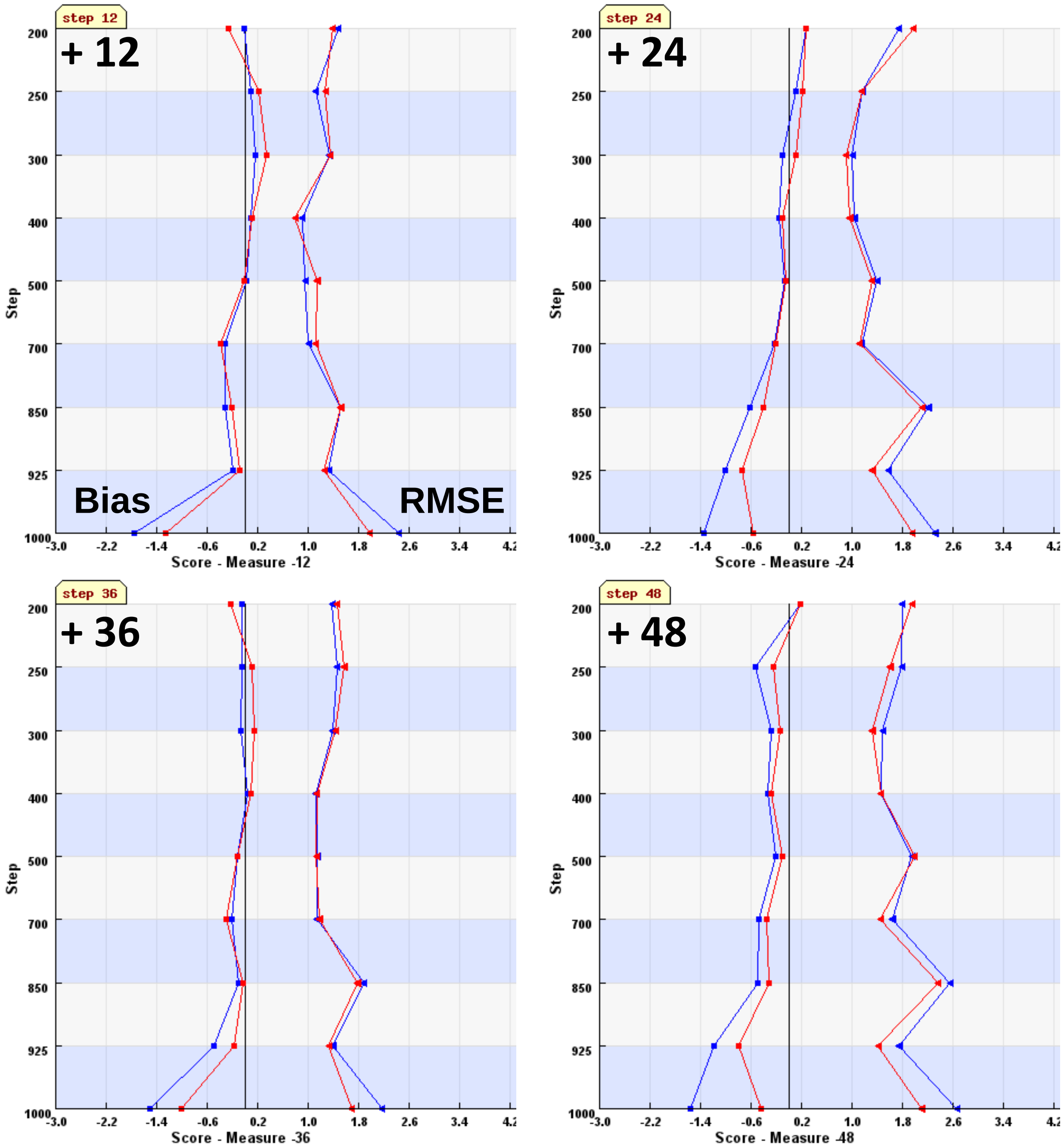




- Improved CE scores except afternoons (comparable at that time)
- Little difference is observed between CE-C and CE-A scores

- RMSE are lower for C-RK at day time, otherwise comparable
- Magnitude of C-RK bias is also lower at day time, otherwise no systematic difference

Temperature: upper-air scores for November 2013

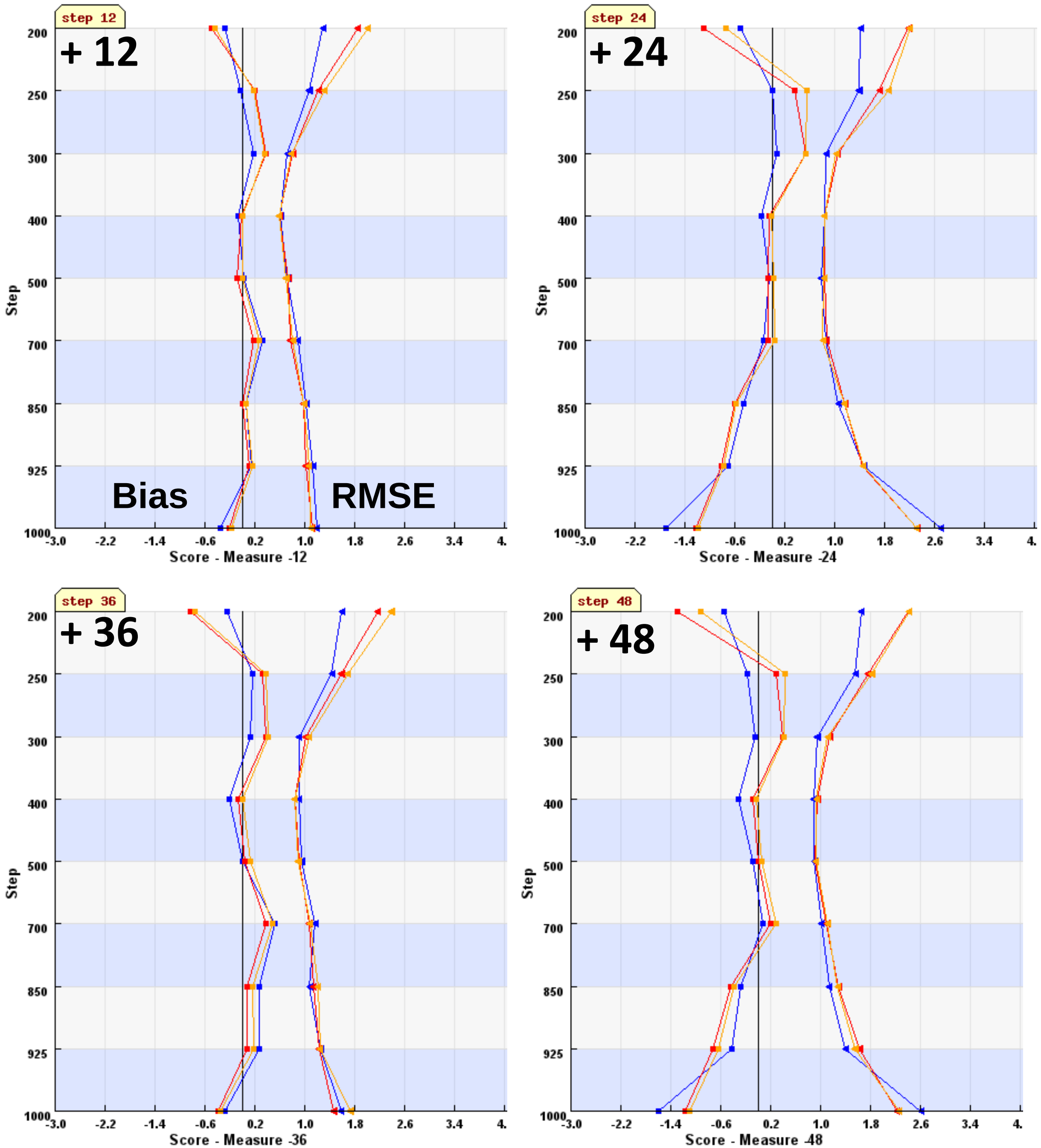


Upper-Air Temperature:

1. At noon: CE-C has better scores near the surface, at higher levels scores are comparable

2. At midnight: CE-C is noticeably better up to 850 hPa level, at higher levels scores are comparable

Temperature: upper-air scores for June 2013

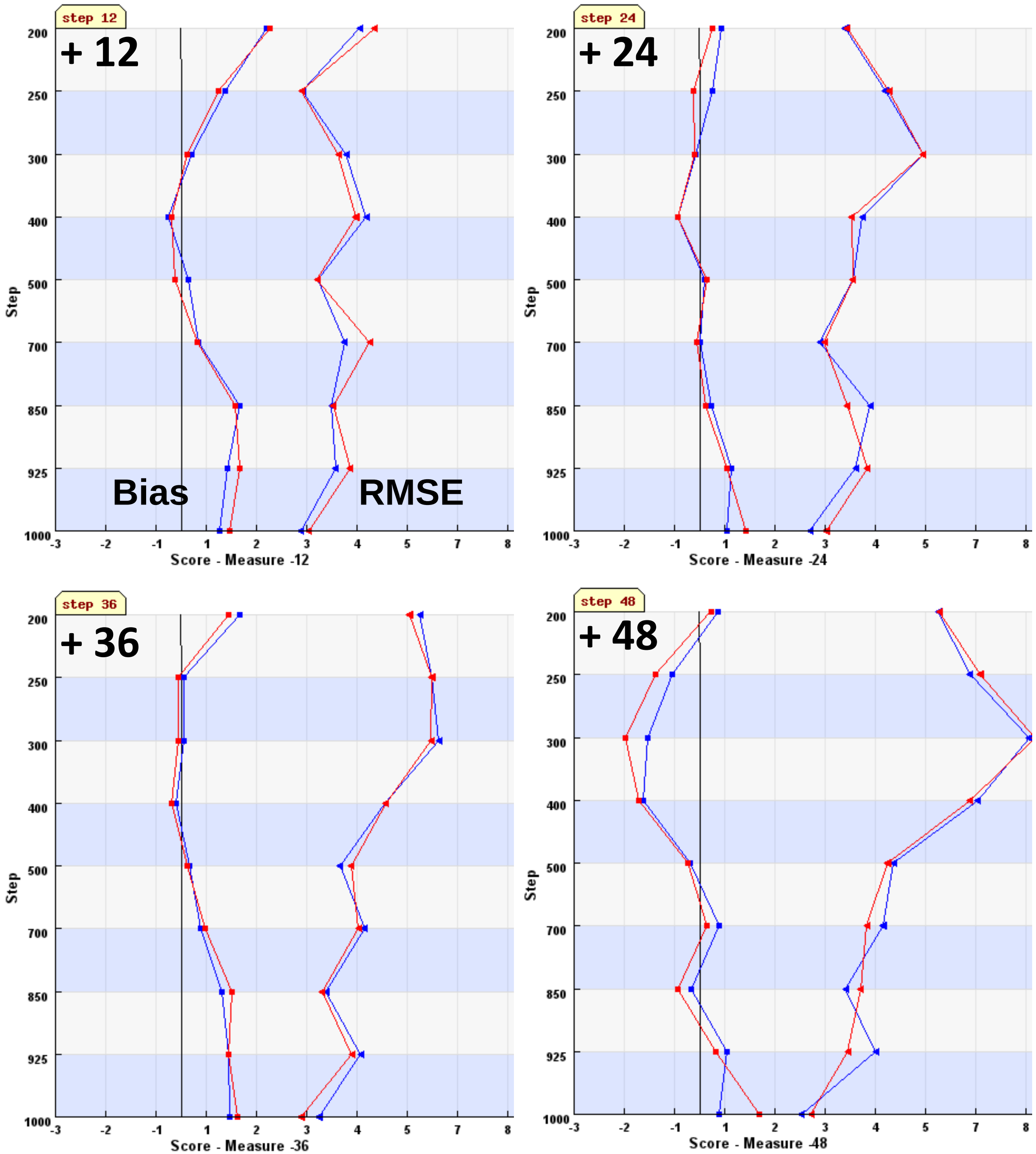


Upper-Air Temperature:

1. At noon: below 300 hPa level scores are similar, at and above 300 hPa the Bias of CE-C is higher

2. At midnight: the CE-C model has better scores at the surface, between 925 and 300 hPa scores are comparable, above 300 hPa C-RK scores are better

Wind Speed: upper-air scores for November 2013

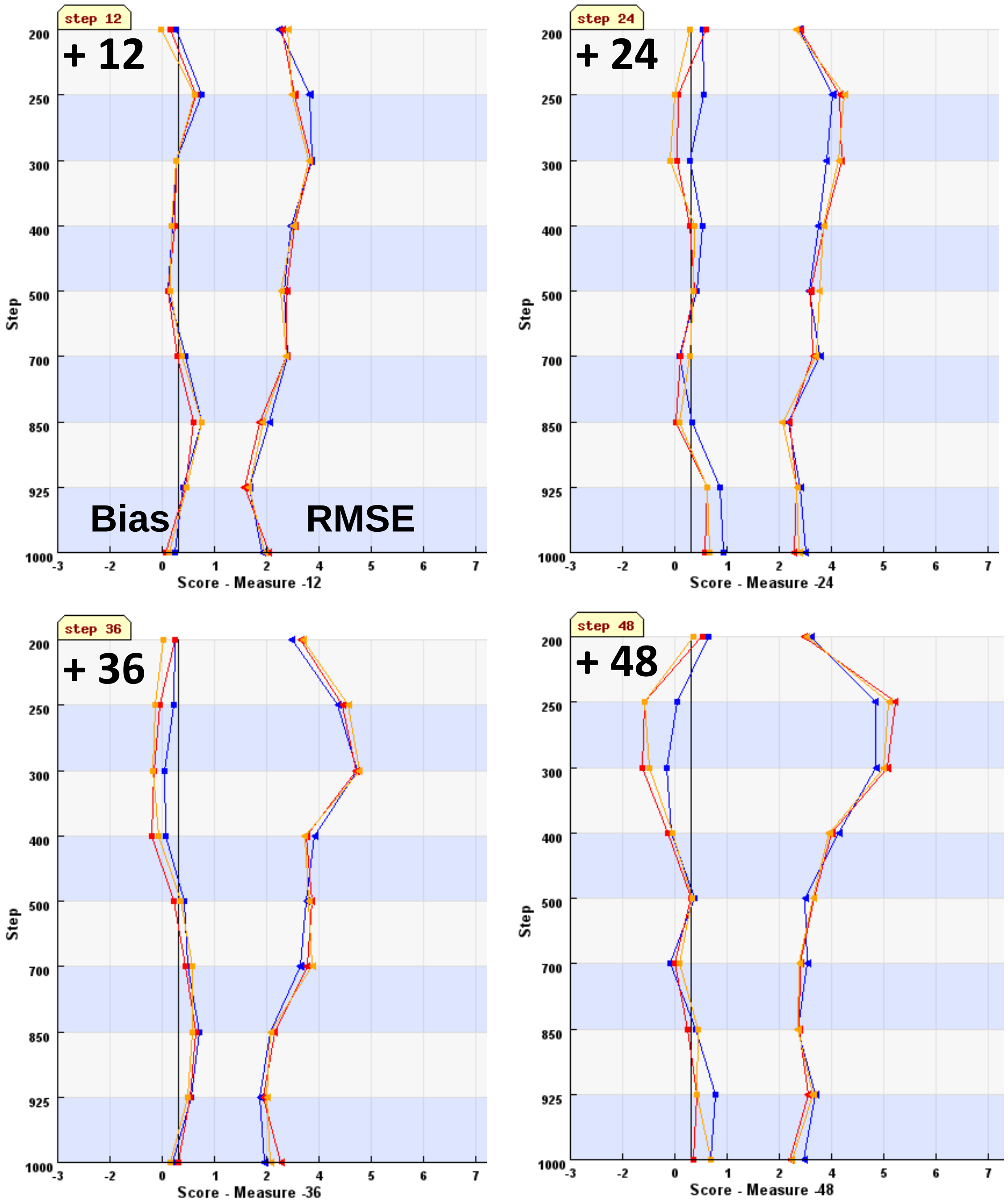


Upper-Air Wind Speed:

1. At noon: scores of CE-C and C-RK models are similar

2. At midnight: CE-C Bias and RMSE near the surface are larger, at higher levels the scores are comparable

Wind Speed: upper-air scores for June 2013



Upper-Air Wind Speed:

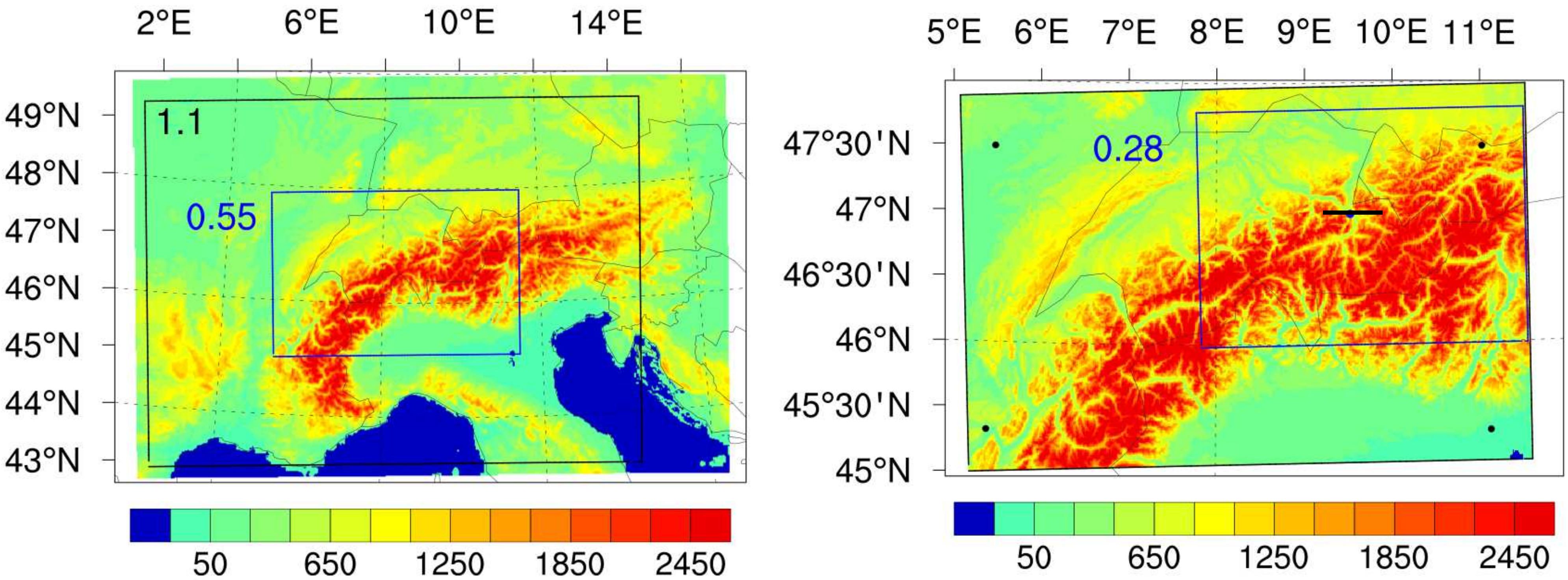
1. At noon: scores of each model are similar

2. At midnight: the Bias and RMSE of CE-C is lower near the surface, in the mid-troposphere scores are similar, and in the upper troposphere C-RK scores are slightly better

3. CE-C tends to have higher bias at 300 and 250 hPa levels

Realistic flow over the Alps in high-resolution simulations

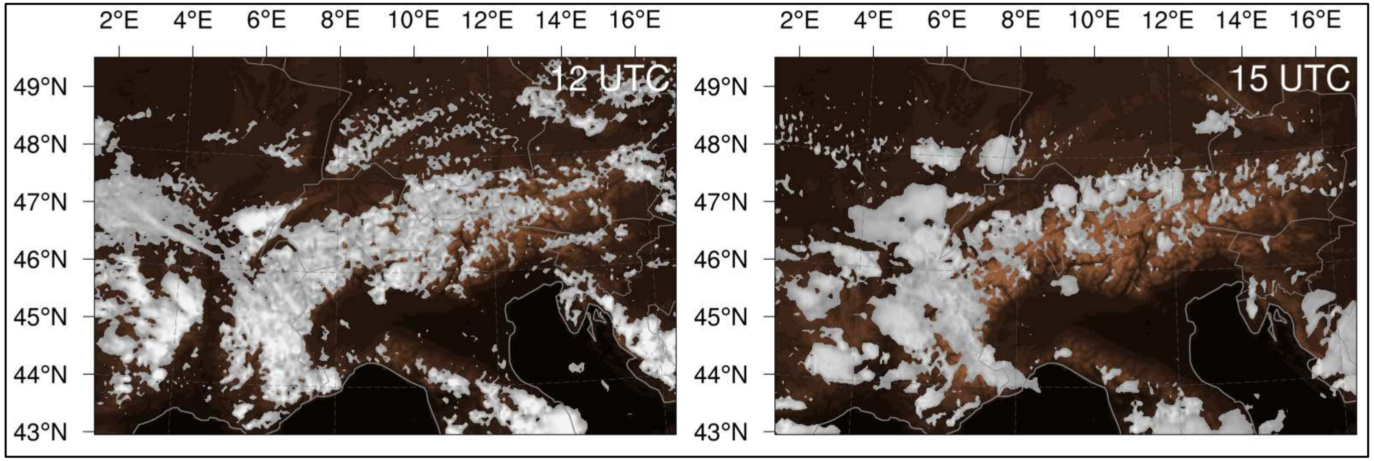
Setup of high resolution simulations



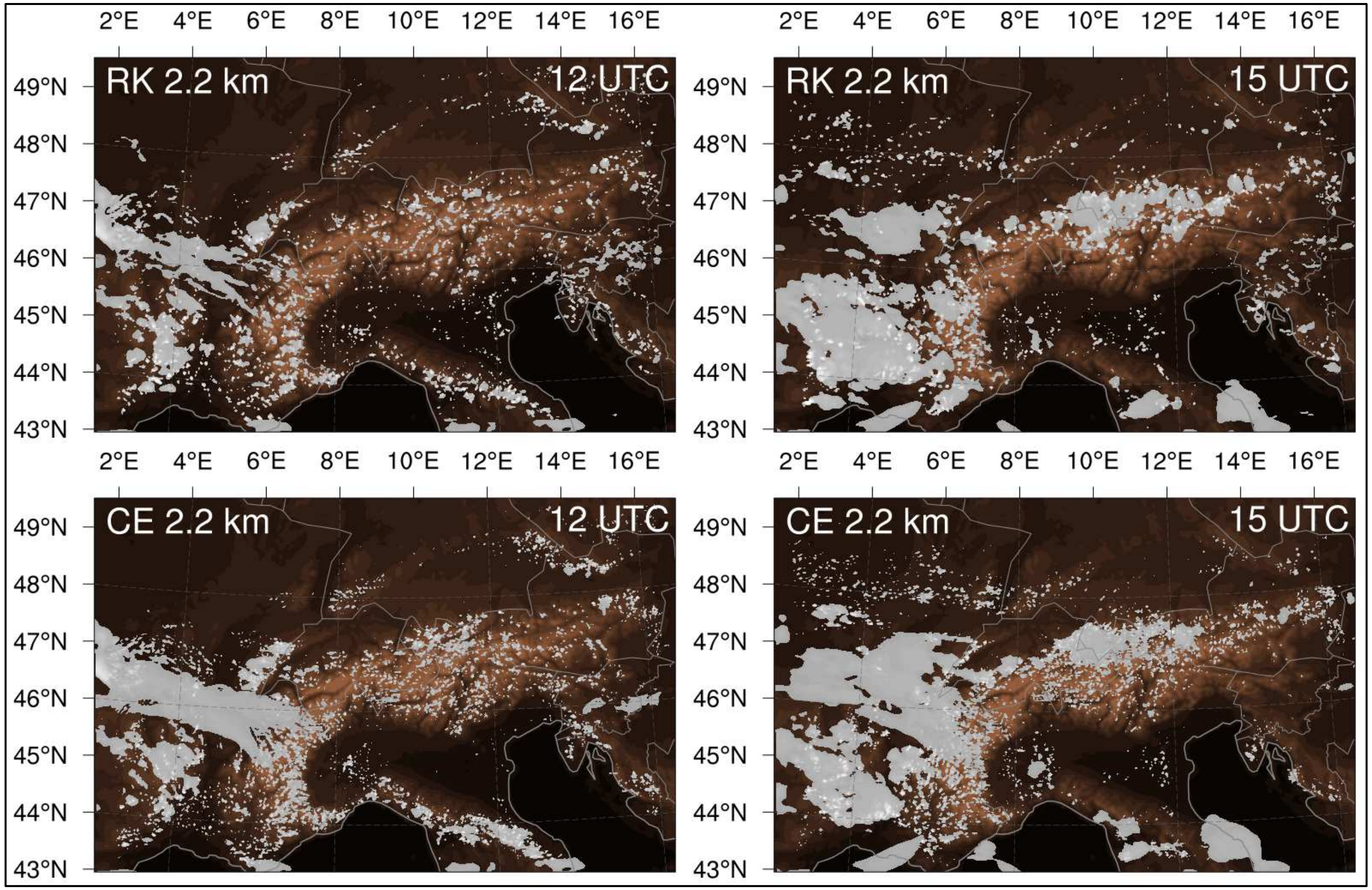
Computational domains employed in this study.
The four black markers (dots) in the right panel indicate corners of the averaging area for statistics.

Grid resolution	# W-E points	# N-S points	# Vertical levels	Lateral absorber width	dt	B. C. update frequency	Parent domain	Simulation start time
2.2 km	520	350	60	40 km	12 s	60 minutes	7.0 km	0 UTC
1.1 km	864	640	60	32 km	4 s	30 minutes	2.2 km	4 UTC
0.55 km	864	576	60	25.6 km	2 s	15 minutes	1.1 km	6 UTC
0.28 km	1000	720	60	20.5 km	1.5 s	15 minutes	1.1 km	6 UTC

Cloud Cover at 12:00 and 15:00 UTC



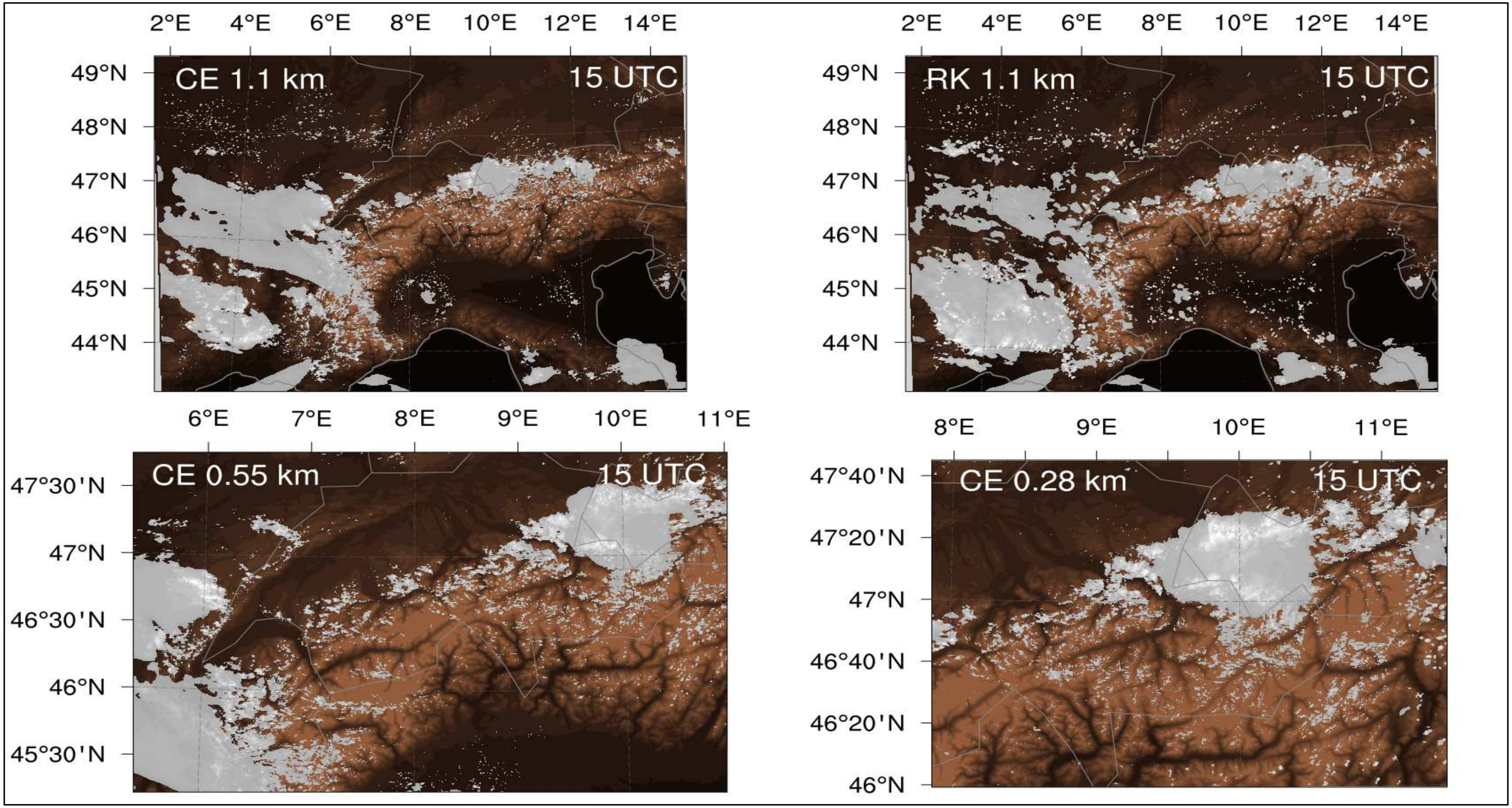
Meteosat albedo (grayscale) with underlying topography.



Model-derived cloud cover from C-RK (top) and CE-C (bottom) at 2.2 km grid resolution from total liquid and ice water.

Quite similar timing of convection in 2.2 km simulations for both models, but the models develop too little shallow clouds at 12 UTC.

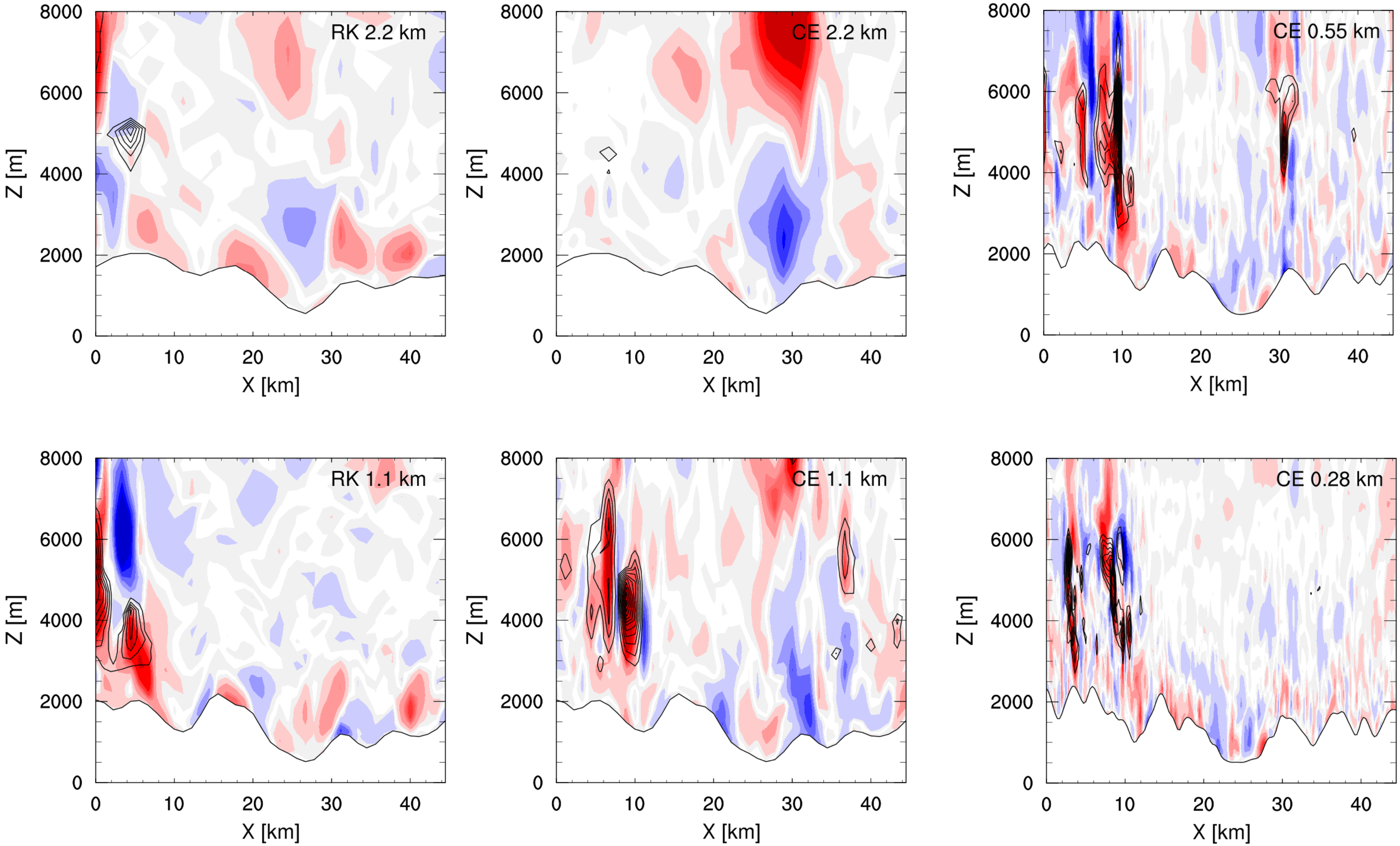
Cloud Cover: 1.1, 0.55, and 0.28 km simulations



Cloud cover (grayscale) at 15 UTC from C-RK (1.1 km) and CE (1.1, 0.55 and 0.28 km).

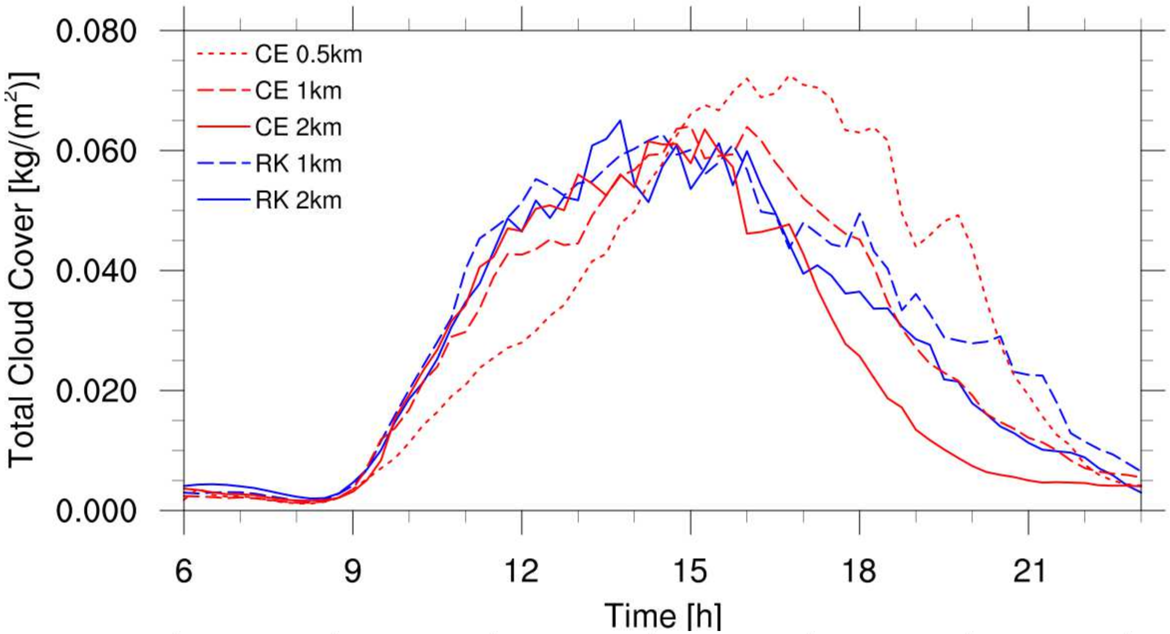
Overall similarity between 'large' scale cloud structure between RK and CE, but many differences in smaller scale.

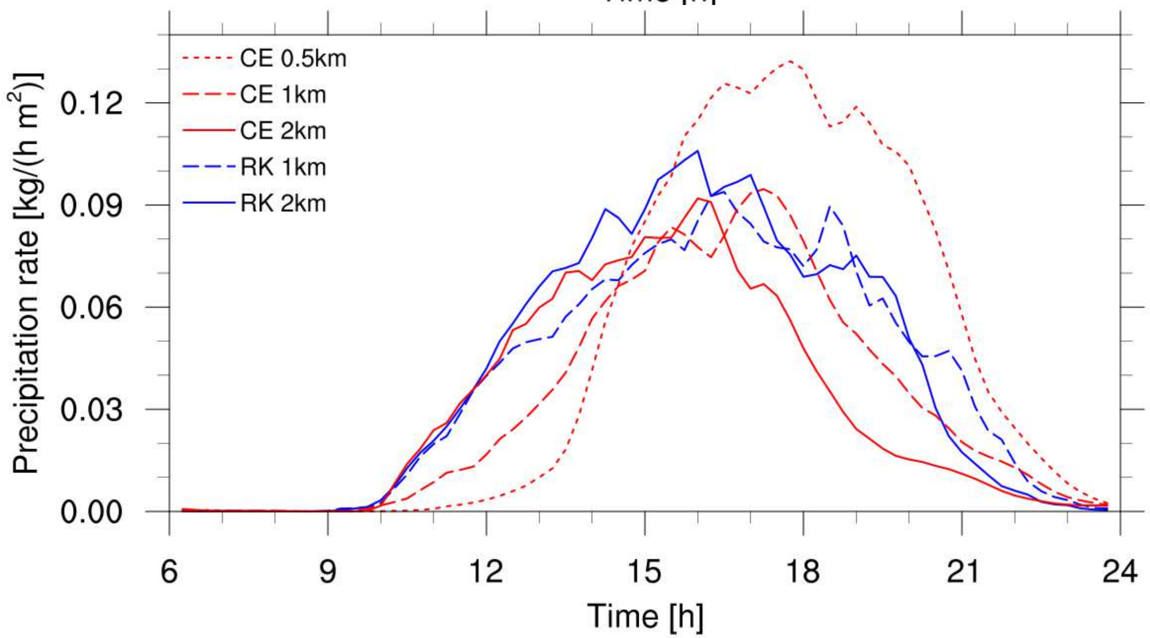
Vertical cross sections across the Rhine Valley: 15 UTC



Vertical velocity (color) and liquid water content (contours every 0.25). RK: 2 left panels, CE: 2 middle and 2 right panels.

TCC and Precipitation Rates





Top: Time series of horizontally averaged total cloud cover for different model setups. Data every 15 min.

Bottom: Time series of horizontally averaged precipitation rates for different model setups

Extended abstract - 34th International Conference on Alpine Meteorology, Reykjavík, Iceland, 18-23 June 2017:

Compressible EULAG solver for limited-area numerical Alpine weather prediction in the COSMO consortium

Damian K. Wójcik, Bogdan Rosa, Michał Z. Ziemiański

Plans and Summary

Plans

In order to deliver an operational weather prediction package to COSMO several tasks shall be completed:

- Model restart capability
- Tuning of parameterizations (see presentation of Bogdan Rosa)
- Source code adjustment to the COSMO Community Standards
- Collection of experiences from operational runs in IMGW-PIB
- Model will be given to COSMO Consortium by September 2018

Summary

- From technical viewpoint both anelastic and compressible-implicit EULAG models have been coupled to the COSMO framework, including the recently-released 5.04 h version
- The issue of the positive bias for 2-m dew point temperature, observed with the new 5.04 framework of COSMO, is being investigated
- Application of the pressure absorber allowed to improve pressure forecasts
- Performed verification leads to conclusion that CE-C model forecasts are close to observations, and are competitive with respect to COSMO R-K
- A robustness of EULAG numerics allows to perform simulations with computational grid step equal 280 m over steep orography (also using the compressible-implicit solver)
- In this experiment delay of convection development is observed in 2.2 km simulations (both models), in particular too little couds are observed in the morning
- In finer CE-C simulations large scale clouds becomes consistent with clouds from coarser simulations in the afternoon
- An explicit formulation of vertical advection limits time step size during convective weather