10.6 HIGH RESOUTION MODELING OF THE APLINE FLOWS USING EULAG ANELASTIC MODEL

Bogdan Rosa*[1], Marcin J. Kurowski[1], Zbigniew Piotrowski[1,2], Andrzej Wyszogrodzki[2], and Michał Ziemiański[1]

[1]Institute of Meteorology and Water Management, Poland
[2]National Center for Atmospheric Research, USA

1. INTRODUCTION

As computational capabilities of supercomputers continue to grow, resolution of mesoscale models for numerical weather prediction (NWP) systematically increases. Currently, spatial resolution of contemporary NWP models approaches 1 km. Although higher resolution allows representing steep slopes of the terrain more adequately, it also involves necessity of employing more sophisticated numerical techniques for reliable and robust modeling of the flows over such complex terrain.

For very high resolutions the models become also able to explicitly represent convective processes. In this context it is interesting to explore the models' capability for representing influence of complicated orography on convection.

Here, we present the results of the very high resolution simulations of convection over the south-western Alps in the regime of relatively weak external forcing. The main goal of the study is to determine effect of grid resolution on modeling of convective processes. The focus is on the inter-comparison of the simulations performed with 2.2, 1.1 and 0.55 km horizontal grids as well as comparison with observational data. The simulations have been performed using model EULAG (Smolarkiewicz and Margolin 1998, Grabowski and Smolarkiewicz, 2002, Prusa and Smolarkiewicz 2003, Smolarkiewicz 2006, Prusa et al. 2008 and the references therein). EULAG is a non-hydrostatic anelastic code developed in National Center for Atmospheric Research (NCAR) and is a prospective candidate for dynamical core of the future operational weather prediction model COSMO (COSMO: Consortium of Small Scale Modeling, grouping some of European national weather services *www.cosmo-model.org*).

2. EXPERIMENTAL SETUP

The EULAG experiments have been performed for three different horizontal resolutions of 2.2 km, 1.1 km and 0.55 km. The simulations were driven using data coming from the operational run of the COSMO2 model of MeteoSwiss working with horizontal resolution of 2.2 km.

COSMO is a nonhydrostatic mesoscale NWP model, based on the Runge-Kutta dynamical core (Doms and Schättler, 2002). COSMO2 was run with all operational parameterizations of physical processes, including interactively calculated representation of surface fluxes. The domain of 23 km height was employed, with the terrain-following coordinate system proposed by Gal-Chen and Sommerville (1975) for its 61 non-uniformly distributed levels.

The setup of EULAG 2.2 km simulations mimics the setup of the COSMO2 model. It employs the same numerical grid, computational domain and orography data. For the larger resolutions (1.1 km and 0.55 km), the grid point positions are constructed by halving the grid distances of 2.2 and 1.1 km model configurations, respectively. All simulations employ the same vertical levels. Horizontal domain for 1.1 km resolution simulation is only slightly smaller comparing the 2.2 km resolution configuration, while the domain for the 0.55 km configuration contains about 25% of the original domain, centered over the SW Alps. The orography data with 1.1 km and 0.55 km resolutions were derived from the 90 m Shuttle Radar Topography Mission (SRTM) (Rodriguez et al. 2005)

The initial and boundary conditions for the EULAG simulation are derived from the operational run of the COSMO2 model. Boundary conditions both for advection and elliptic pressure equations are updated in time, employing a linear interpolation between the hourly data. At the top of the computational domain, open boundary conditions and a sponge layer (above 15 km) for dumping reflecting waves are imposed. The Eulerian advection scheme uses the MPDATA approach (Smolarkiewicz and Margolin, 1998; Smolarkiewicz, 2006 and references therein).

The EULAG simulations apply a limited set of physical parameterizations. As there is no soil model employed, the surface fluxes of sensible and latent heat calculated by COSMO2 were used for all simulations, interpolated to 1.1 km and 0.55 km grid resolutions, as necessary.

The EULAG simulations at resolutions of 2.2 km and 1.1 km have been performed with a representation of boundary layer processes in

* *Corresponding author address*: Bogdan Rosa, IMGW, ul. Podleśna 61, 01-673 Warszawa, Poland; email: bogdan.rosa@imgw. pl

a form of a TKE (Turbulent Kinetic Energy) scheme (Margolin et al., 1999), or using an ILES (Implicit Large Eddy Simulation) (Grinstein et al. 2007) mode with a prescribed form of the surface fluxes. Due to computational costs, simulations at the highest resolution of 0.55 km have been performed only in the ILES mode. To represent moist processes, a warm rain microphysics scheme (see Grabowski and Smolarkiewicz, 2002) is applied.

Governing equations of motion were integrated with time step depending on horizontal grid resolution. For 2.2 km time step was set to 6 seconds, for 1.1 and 0.55 km resolutions to 3 seconds (as we do not run simulation with TKE at 0.55 km resolution). For integration of equations representing moist processes, the time step was shorter, namely 2 seconds, for the 2.2 km resolution.

3. Meteorological situation in the Alpine region - 12 July 2006

The study presented here concerns the case of mountain convection over the south-western (SW) Alps on 12 July 2006. During that day, the Alpine region remained in the vicinity of the cold front, relatively fast moving and active over Northern Europe and Baltic, but almost quasi stationary in the Alpine area. The region was covered by a shallow surface trough related to a relatively shallow low pressure system over the Mediterranean Sea and Anatolia (not shown).

The pictures from the geostationary Meteosat satellite (Fig. 1, a superposition of visible and infrared data) show practically no clouds over the SW Alps at 09.00 UTC, (it is confirmed by the picture from a NOAA satellite, not shown). There is a hint of frontal layer clouds further north, and especially over Poland, at that time.

At 12.00 UTC, the Meteosat picture shows that a convection started to develop over the Alps, mainly over its SW and Eastern parts, and is already locally deep and vigorous. The convection intensifies and spreads over the Alps and its SW part, quickly, so that at 15.00 UTC the anvils of Cumulonimbus clouds cover significant part of the Alps. The strong tendency to convection organization is also seen in a form of clustering, so that at 18.00 UTC the whole Alpine area and its vicinity are covered by the clusters of deep convective clouds.

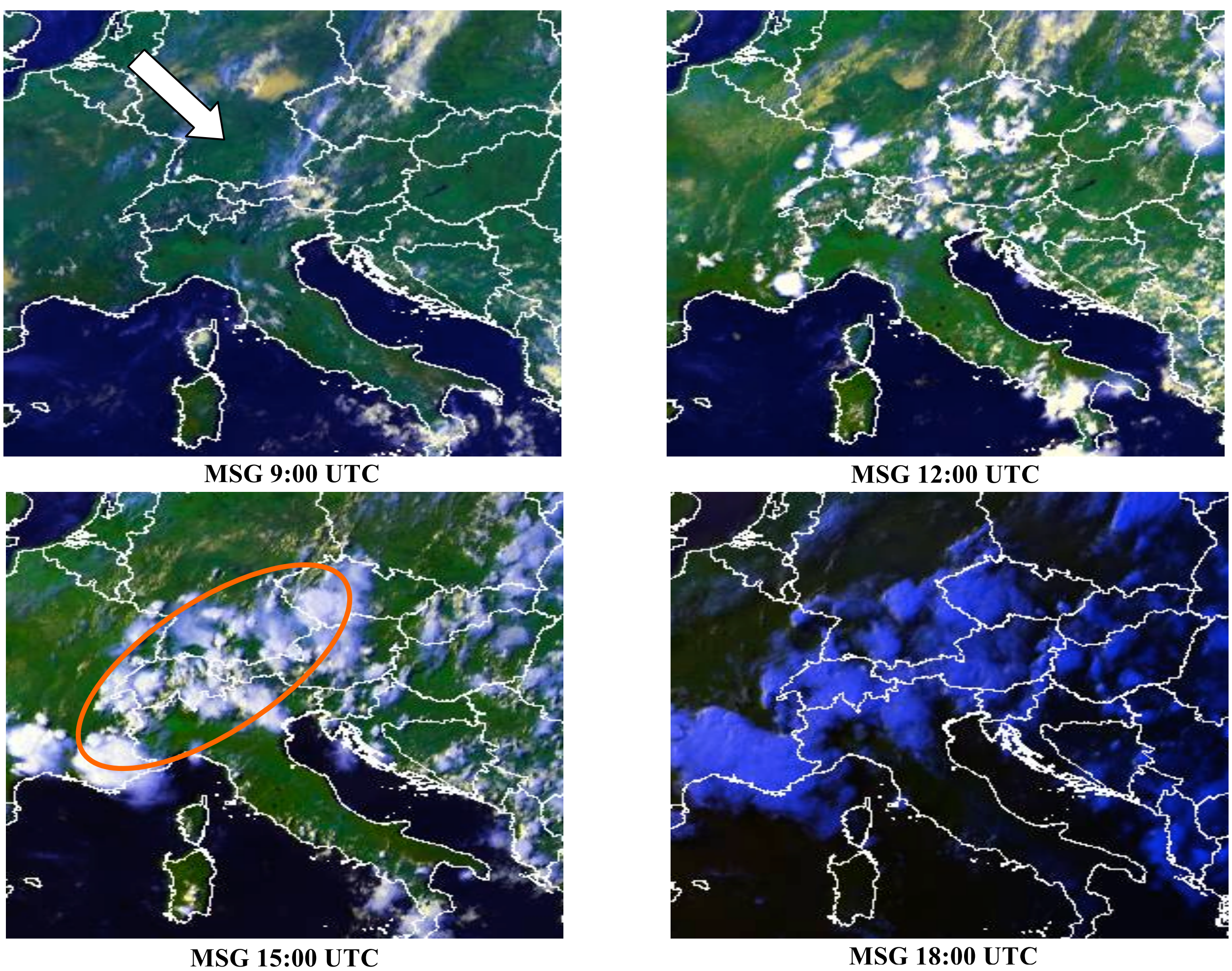

Figure 1. Time evolution of convection in sequence of MSG satellite images (visible and infrared in false colors) - 12 July 2006. Onset of deep convection in the SW Alpine area occurs shortly before 12UTC, strong development is observed between 12 and 15 UTC.

4. Results from numerical modeling

First, we present results of the simulations at the resolution of 2.2 km, performed both with EULAG and COSMO models. Figure 2 shows 3-dimensional plots of streamlines (red) and the isosurface of cloud water mixing ratio for the threshold of 0.05 g/kg (grey), representing an extent of cloud volume, at 15.00 UTC. At that time, the actual convection is already well developed all over the Alps. It is clearly seen, that both for COSMO and in EULAG simulation, the extent of cloud volume is substantially smaller then in the MSG images presented in Fig.1. More, the area of SW Alps, where the actual convection is especially vigorous, is practically cloud free for all simulations. It is also the case for 12.00 and 18.00 UTC (not shown). It is seen also, that the EULAG simulation results do not depend significantly on the representation of the subgrid scale mixing, employed.

The streamline pattern is generally similar for COSMO and EULAG simulations, indicating generally similar flow pattern, but there are also clearly seen differences, e.g. in the area south of Alps. There are no significant differences between streamlines for two EULAG simulations (Figures 2a and 2b). Some differences between them likely result from additional viscosity introduced by TKE parameterization.

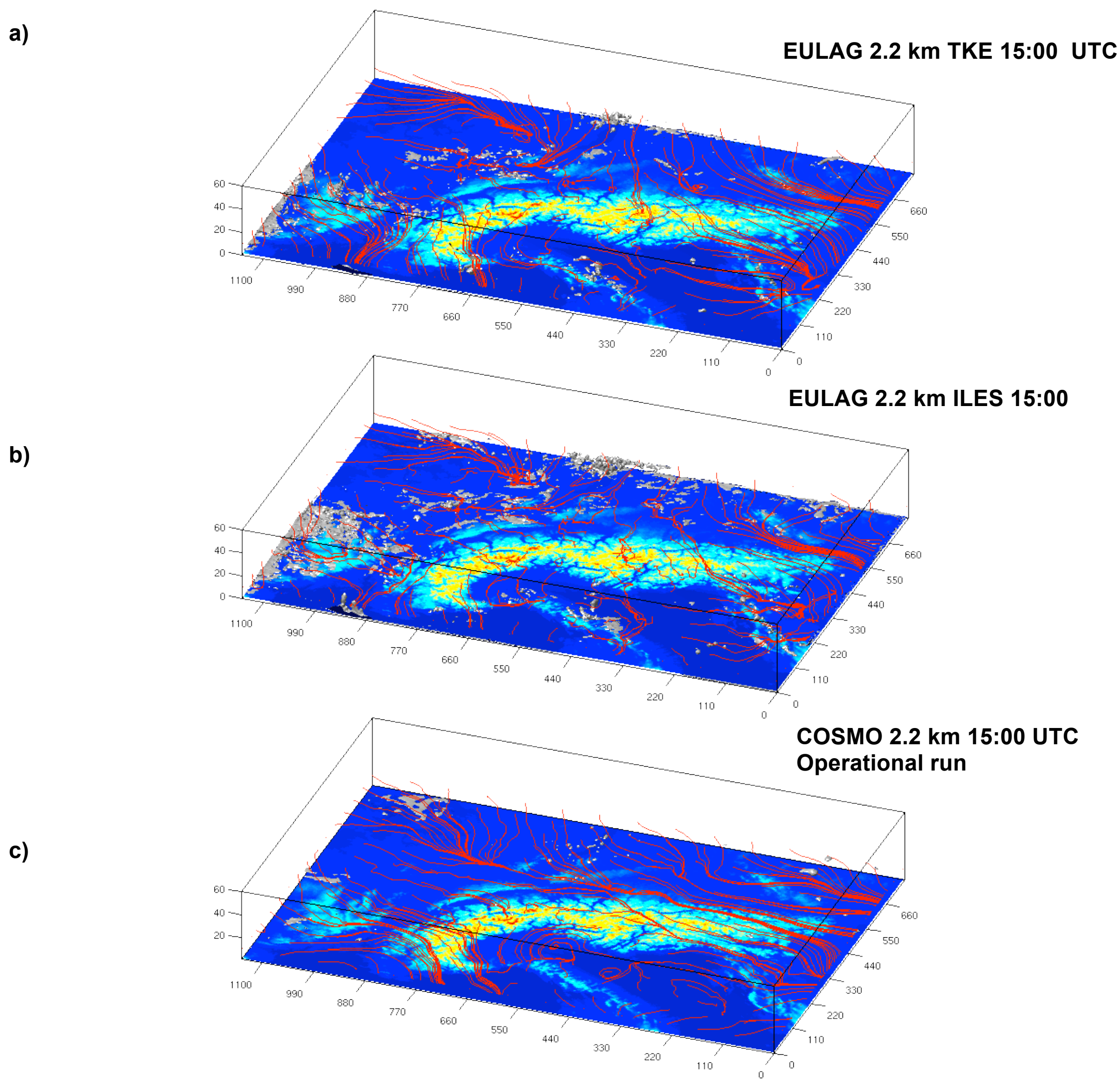

Figure 2. Results of the simulations performed at resolution 2.2 km using both EULAG and COSMO models: a) EULAG – simulation with TKE, b) EULAG - ILES run, c) solution from the operational run of the COSMO model with all parameterizations on. The red lines show instantaneous streamlines. The grey isosurfaces represent constant value of cloud water for mixing ratio of 0.05 g/kg.

Additionally, Figure 3 presents a sequence of plots comparing the time evolution of specific humidity for EULAG-TKE (left column) and COSMO (right column) models. Vertical cross-section is aligned roughly along constant latitude at 64° 30’ N. The EULAG simulation starts at 6 UTC using the initial fields from COSMO, so at the beginning both fields are identical. The sequence of plots presenting the solutions from EULAG model (left column) shows the situation after 3, 6 and 9 hours of simulation. There are two important differences between simulations with EULAG and with COSMO. The humid towers clearly seen in EULAG simulation, and related to convection activity, are not present in the solution from the COSMO model. The second difference is related to the boundary layer. COSMO produces well mixed boundary layer up to ~1 km above ground. In EULAG the structure of boundary layer, ranging between 500 m and 1.5 km, is less uniform. The differences show an influence of different parameterization of surface layer processes.

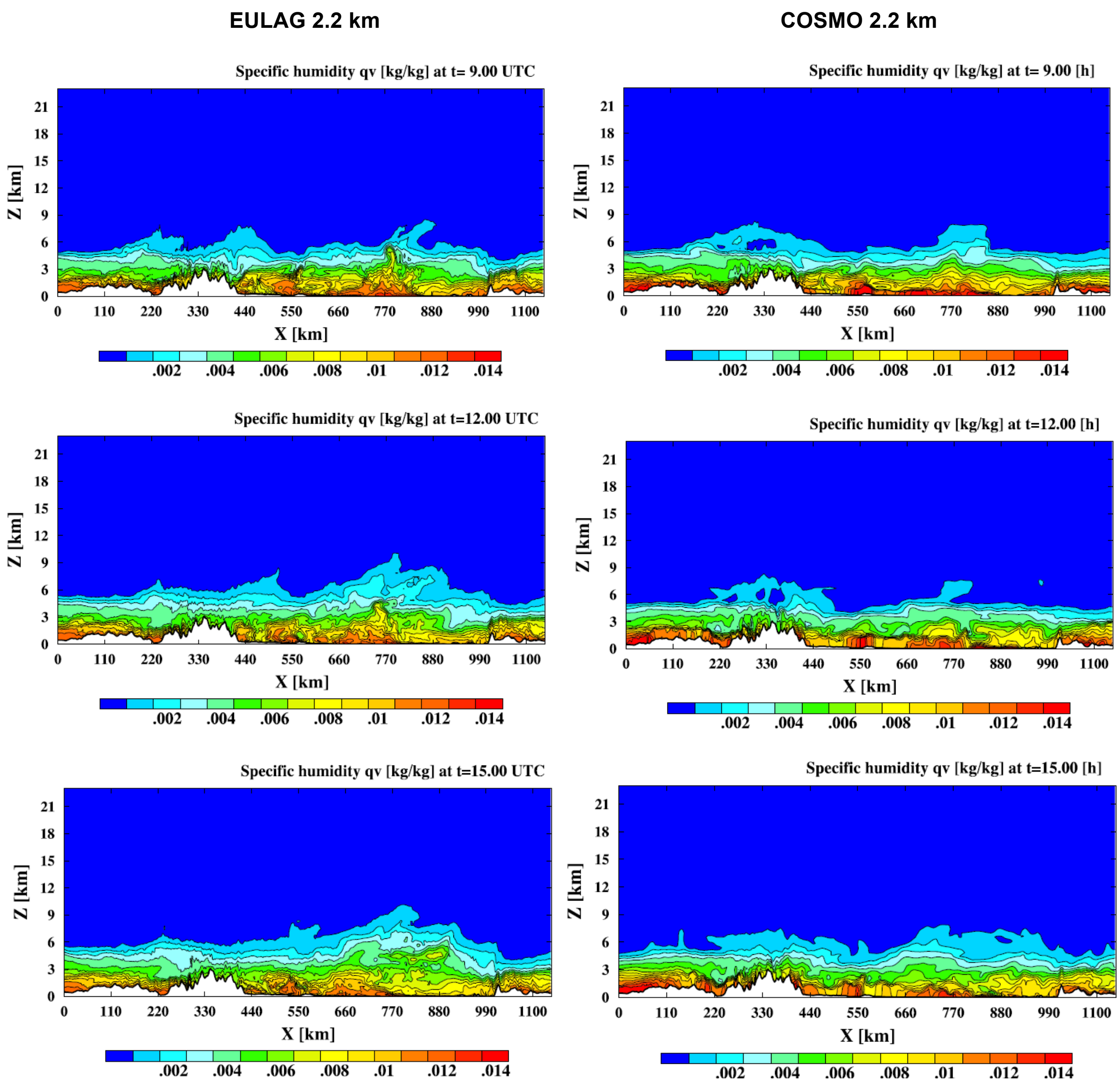

Figure 3. Time evolution of specific humidity. The sequence of pictures presents vertical cross-section along the 64° 30’ N. Results from numerical simulations computed using EULAG (left column) and COSMO (right column) at the same horizontal resolution 2.2 km.

Figure 4 presents results of two EULAG ILES simulations performed at higher resolutions, namely 1.1 km (left column) and 0.55 km (right column). Due to the numerical cost, the size of the domain for resolution of 0.55 km is reduced. The results significantly differ from simulations at 2.2 km resolution, where all simulations failed to represent convection over the SW Alps, regardless of the parameterization, employed. Now, already for the resolution of 1.1 km, a production of a mass of convective clouds over the SW Alps is seen, and the timing of the modeled convection initiation agrees with observations. The simulation employing the 0.55 km resolution generally reproduces this result, even if the convection is slightly weaker and sparser than in 1.1 km case. On the other hand, it is worth noting that none of the simulations, even at resolutions of 1.1 km and 0.55 km, is able to represent accurately the observed afternoon clustered cumulonimbus convection organization seen on satellite images presented in (Fig. 1). At each control hour on Fig. 4, the modeled convection shows sparser cumulus organization in the Alpine areas than at the corresponding satellite observations. The late afternoon observations at 15:00 UTC and 18:00 UTC indicates development of much stronger clustered cumulonimbus structures which are absent in the simulations. The reason for this model deficiency is unclear at this time and may be related to still coarse horizontal resolution or inadequate for this problem warm rain microphysics scheme.

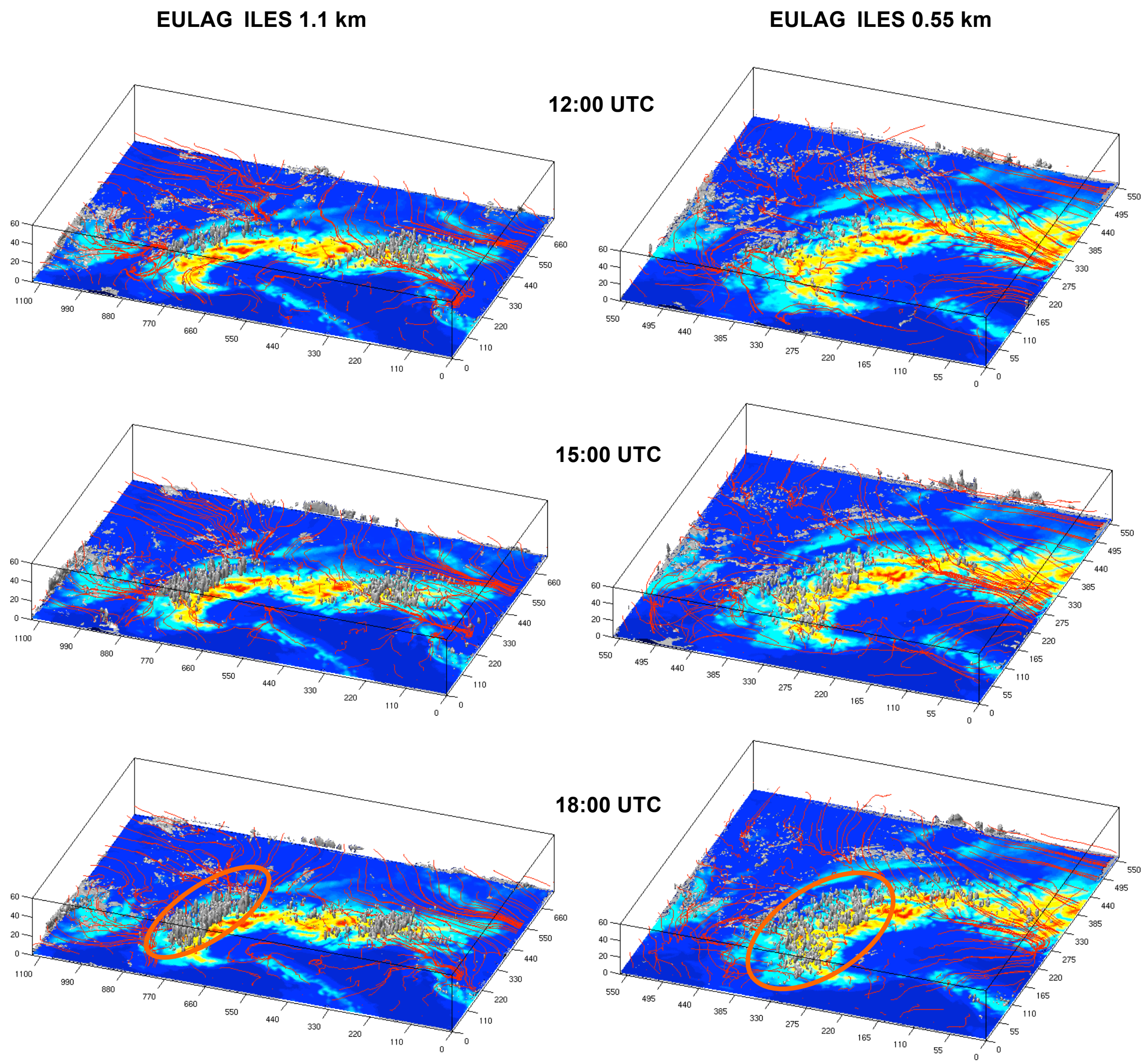

Figure 4. Results from the EULAG simulations of moist convection over the Alpine topography carried out for 12 July 2006. The left column presents time evolution of the flow and cloud formation at 1.1 km horizontal resolution. In the right column the analogous results for 0.55 km and reduced domain are shown. All the variables are plotted in the same manner as in Fig. 2.

5. Performance of the model EULAG

The tests have been performed in the Swiss National Supercomputing Centre and in the National Center for Atmospheric Research (NCAR USA). We examined performance of two CRAY machines XT4 and its next generation XT5m. The XT4 system consists of 2 cabinets, containing 8 service processing elements (PEs), subdivided into 4 service blades, and 160 quadcore nodes giving 640 compute PEs, subdivided into 40 compute blades. The Cray XT5m system utilizes 2-dimensional (2D) torus architecture, optimized for superior application performance between 500 and 6,000 processing cores. The numerical efficiency (wall clock time) from performed simulations is given in Table 1.

Table 1 Performance of the EULAG model tested at three different grid resolution and using two different machines Cray XT4 and Cray XT5m.

Horizontal resolution	Parameterization of sub-grid scale processes	Domain size in grid points	# of processors and machine	Forecast	Wall clock time
2.2 km	ILES	520 x 350 x 61	500 – CRAY XT4	12 hours	1 h 11 min
2.2 km	TKE	520 x 350 x 61	500 – CRAY XT4	12 hours	1 h 26 min
1.1 km	ILES	1020 x 680 x 61	600 – CRAY XT4	12 hours	9 h 50 min
1.1 km	TKE	1020 x 680 x 61	600 – CRAY XT5m	12 hours	9 h 50 min
0.55 km	ILES	1020 x 1020 x 61	400 – CRAY XT5m 900 – CRAY XT5m	12 hours 12 hours	17 h 47 min 8 h 31 min

6. CONCLUSIONS

The results of the study, presented above, show a significant influence of the model resolution on numerical representation of the mountain convection in the regime of a weak external forcing. The results suggest that the horizontal grid step of 2.2 km is not sufficient for a realistic representation of such convection. An increase of the model resolution to the grid size of 1.1 km, and beyond, allows for a realistic representation of the convection initiation and development, at least for its earlier stages, even for relatively simple physical parameterizations, employed. The reasons, why our simulations were not able to reproduce the strong cumulonimbus convection organization and the modeled cloud fields were slightly weaker and sparser need further studies.

7. ACKNOWLEGEMENTS

This work was supported by National Center for Atmospheric Research under the RSVP program. Computing resources are provided also by National Center for Atmospheric Research (CISL-35751010 and CISL-35751014). We are also grateful to Dr. Wojciech Grabowski and Dr. Piotr Smolarkiewicz for the helpful advises regarding technical and physical aspects of the numerical experiments and Dr. Oliver Fuhrer for providing the full reference set of COSMO data for our simulations.

8. REFERENCES

1. Smolarkiewicz, P.K., and L.G. Margolin, 1998: MPDATA: a finite difference solver for geophysical flows. *J. Comput. Phys.*, **140**, 459–480.
2. Grabowski, W.W., and P.K. Smolarkiewicz, 2002: A multiscale anelastic model for meteorological research. *Mon. Weather Rev*., **130**, 939–956.
3. Prusa, J., and P.K. Smolarkiewicz, 2003: An all-scale anelastic model of geophysical flows: dynamic grid deformation. *J. Comput. Phys.*, **190**, 601–622.
4. Smolarkiewicz, P.K., 2006: Multidimensional positive definite advection transport algorithm: an overview. *Int. J. Numer. Meth. Fluids,* **50**, 1123–1144.
5. Prusa, J.M., P.K. Smolarkiewicz, and A.A. Wyszogrodzki, 2008: EULAG, a computational model for multiscale flows. *Computers and Fluids,* **37**, 1193–1207.
6. Doms G., and U Schättler, 2002: A Description of the Nonhydrostatic Regional Model LM. Printed at Deutcher Wetterdienst, Germany.
7. Gal-Chen, T., and C.J. Somerville, 1975: On the use of a coordinate transformation for the solution of the Navier–Stokes equations. *J. Comp. Phys.,* **17**, 209–228.
8. Rodriguez, E., C.S. Morris, J.E. Belz, E.C. Chapin, J.M. Martin, W. Daffer, and S. Hensley, 2005: An assessment of the SRTM topographic products, Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California, 143 pp.
9. Margolin, LG, P.K. Smolarkiewicz, and Z. Sorbjan, 1999: Large-eddy simulations of convective boundary layers using nonoscillatory differencing, *Physica D,* **133**, 390–397.
10. Grinstein F.F., L.G Margolin, W.J. Rider, 2007: Implicit Large Eddy Simulations, Cambridge University Press, 546 pp.