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Supercomputer Technologies as a Tool for High-resolution Atmospheric Modelling towards the Climatological Timescales

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Estimation of the recent and future climate changes is the most important challenge in the modern Earth sciences. Numerical climate models are an essential tool in this field of research. However, modelling results are highly sensitive to the spatial resolution of the model. The most of the climate change studies utilize the global atmospheric models with a grid cell size of tens of kilometres or more. High-resolution mesoscale models are much more detailed, but require significantly more computational resources. Applications of such high-resolution models in climate studies are usually limited by regional simulations and by relatively short timespan. In this paper we consider the experience of the long-term regional climate studies based on the mesoscale modelling. On the examples of urban climate studies and extreme wind assessments, we demonstrate the principle advantage of long-term high-resolution simulations, which were carried out on the modern supercomputers.

Keywords: regional climate model, long-term simulations, supercomputer technologies, extreme wind, urban climate, urban precipitation, COSMO.

Introduction

The current state in the numerical weather and climate modelling field reached a level, which often allows to consider this technique as an alternative to traditional climate-related data sets, based on the in-situ observations. Climate models are the parallelized programs that solve the system of differential equations describing the hydrothermodynamics of the atmosphere, ocean, soil and other components of environment. Such system does not have an analytical solution and has to be solved by finite-difference numerical methods, applied for a prescribed model grid. The spacing between horizontal and vertical grid points is a key parameter of the atmospheric models and determines their resolution the scale of the processes, which could be represented explicitly by the basic model equations. Other processes are called as subgrid processes and should be parameterized, i.e. expressed through an additional physical model or empirical approaches.

Decreasing of the grid spacing makes the simulation results more detailed and physical. However, such improvements lead to a huge increase of required computational resources, because a stable numerical solution for a smaller grid step demands a smaller time step according to the Courant criterion. Therefore, the grid spacing of the global climate models is still limited by the first tens of kilometres. It means that only the synoptic-scale processes could be resolved, while the most of the mesoscale processes – e.g. polar lows, sea/lake breezes, convective systems, which are responsible for many severe weather events, – could not be resolved. This is done by atmospheric models with a grid step within a range of 1–10 km (mesoscale models), which are usually applied for limited-area simulations using the dynamical downscaling approach [1], short timespan (case study, one season or few years) and require significant computational resources.

In this short communication, we present a review of our recent studies, based on the long-term simulations with a regional (limited-area) mesoscale climate model COSMO-CLM, carried out on the modern supercomputer complex of Lomonosov Moscow State University [2]. We focus on the specific research opportunities, which are opened by the long-term regional climate

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simulations based on two examples: the first one is an urban climate study for Moscow megacity, and the second one is an extreme wind assessment over maritime region in the Far East of Russia.

1. Model Description and Experiments Design

We used the COSMO-CLM model (ver. 5.0) as the main tool in our studies. COSMO-CLM is the regional climate model developed by German Weather Service (DWD) and CLM-Community ($http://www.clm-community.eu$; [3, 4]). The dynamical downscaling technique for the chain of nested domains was applied in our simulations using ERA-Interim reanalysis data [5] ($\sim 0.75^0$ resolution) as forcing, and the "spectral nudging" technique was applied in order to link the model behaviour to the real large-scale atmospheric dynamics [6, 7].

2. Experiment Results

2.1. Research of the Urban-induced Climate Anomalies of Moscow Megacity

Urban climate effects, such as urban heat island (UHI), are well-studied for surface layer of the atmosphere. However, the most of urban climate studies are based only on episodic observations or short-term numerical simulations. Recent developments of supercomputer technologies have opened new opportunities to study the urban-induced climate features towards the climatological timescale. The investigation of the urban-induced climate features of Moscow megacity based on the long-term mesoscale simulations is presented in details in [8].

In the study for Moscow, the COSMO-CLM model was used for the dynamic downscaling of the reanalysis data for three nested domains (Tab. 1). An urban canopy scheme TERRA_URB [9] was applied to parametrize the urban surface features in simulations for the final domain D3_Mos with 1 km horizontal grid step. Simulations with and without the TERRA_URB scheme (URB/noURB runs) were conducted for 10 summer seasons (2007–2016). Supercomputer "Lomonosov-2" of Lomonosov Moscow State University [2] was used for calculations ($177{\cdot}10^3$ CPU hours in total, see details in Tab. 1).

Table 1. Description of the model domains and the computational resources, used in the modelling studies for Moscow (May–August) (D_Mos) and the Far East of Russia (D_Sak)

Name	Horizontal grid size, cells/km	Horizontal grid step, km	Time step, sec	Nodes used	Computing time for year run, hours
D1_Mos	140x140	12	120	64	5.1
D2_Mos	200x200	3	40	144	14.5
D3_Mos	180x180	1	10	196	39
D1_Sak	145x355	13.2	120	288	20
D2_Sak	228x525	6.6	40	288	60
D3_Sak	300x500	2.2	20	196	-

Comparison between URB and noURB runs confirm the existence and significance on seasonal scales of the various megacity-induced effects, including the UHI extended to the atmospheric boundary layer, the urban breeze circulations and positive urban precipitation anomaly. We have considered these effects in more details due to high-resolution simulations. The difference in summer precipitation sum between URB and noURB runs for a one season is characterized by a chaotic spatial structure [8] caused by the stochastic nature of summer convective showers, but averaging over ten summer seasons reveals a substantial urban-induced anomaly of summer precipitation (by 10% in average over the city). The difference between these simulations could explain a significant uncertainty of urban precipitation effects, indicated in [10].

2.2. Extreme Winds Assessment in the Far East of Russia

An investigation of extreme weather events and wind speeds could be made using the long-term (for decades) simulations and robust statistical estimates of outputs. We have run the long-term experiment similar to the previous one for the Sea of Okhotsk and Sakhalin Island region [11] for the 1985-2014 period (see Tab. 1).

Long-term simulations for domains D1_Sak and D2_Sak allowed to select the cases with the highest winds (more than 25 m/s) according to the "independent storms" technique [12]. For the selected cases a detailed synoptic analysis was performed in order to investigate the typical synoptic patterns favorable for the genesis of extreme wind speeds [11]. Moreover, long-term simulations allowed us to discover a significant ($p > 0.95$) positive trend for the frequency of the wind speed exceeding 20 m/s in the area under study (Fig. 1).

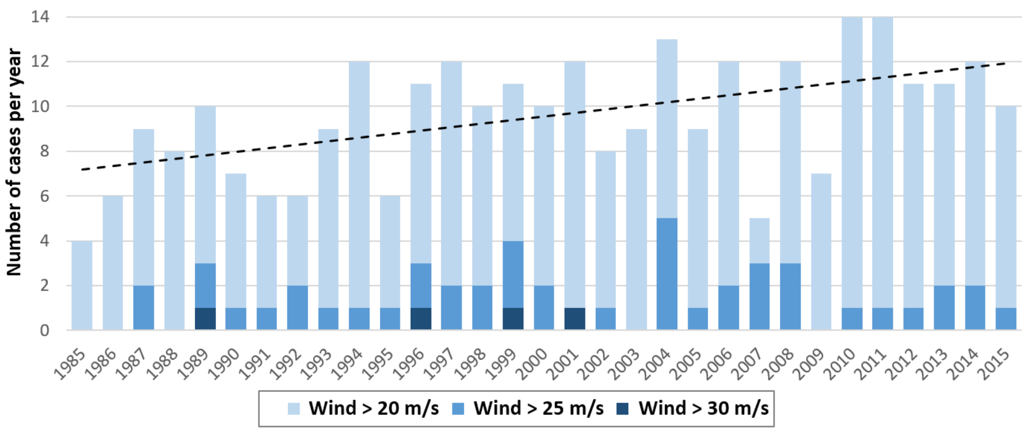

Figure 1. Number of cases with wind speed above thresholds 20, 25 and 30 m/s for 1984–2015 period. The linear trend refers to 20 m/s threshold

Conclusion

Long-term detailed regional climate simulations are opening up a lot of opportunities to Earth science researchers, e.g. estimations of modern and future climate trends, environmental consequences. The main advance of this approach is a suppression of stochastic processes in climate system and a great potential to statistical analysis of weather and climate extremes. Ultimately, namely the development of supercomputer technologies is a prerequisite of successful climate and Earth system research.

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