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Preliminary contributions

ISSUES IN HIGH-RESOLUTION ATMOSPHERIC MODELING IN COMPLEX TOPOGRAPHY – THE HiRCoT WORKSHOP

Problemi atmosferskog modeliranja visoke razlučivosti u kompleksnoj topografiji – HiRCoT radionica

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Abstract: During the past years the atmospheric modeling community, both from the application and pure research perspectives, has been facing the challenge of high resolution numerical modeling in places with complex topography. In February 2012, as a result of the collaborative efforts of the Institute of Meteorology of the University of Natural Resources and Life Sciences (BOKU-Met), the Arctic Region Supercomputing Center (ARSC), the Institute of Meteorology and Geophysics of the University of Innsbruck (IMG) and the enthusiasm of the scientific community, the HiRCoT workshop was held in Vienna, Austria. HiRCoT objectives were to: 1) Identify the problems encountered with numerical modeling at grid spacing lower than 1 km over complex terrain, that is, understand the key areas that are troublesome and formulate the key questions about them; 2) Map out possibilities on how to address these issues; 3) Allow the researchers to discuss the issues on a shared platform (online through a wikipage and face-to-face). This manuscript presents an overview of the topics and research priorities discussed in the workshop.

Key words: High-resolution atmospheric modelling, physical parametrisation, numerical schemes, input and initialization, computational aspects, HiRCoT workshop

Sažetak: Numeričko atmosfersko modeliranje je tijekom zadnjih nekoliko godina, iz perspektive kako fundamentalnog tako i primijenjenog istraživanja, suočeno s izazovom potrebe za numeričkim modeliranjem visoke razlučivosti u kompleksnom terenu. HiRCoT radionica održana je u veljači 2012. u Beču, Austrija kao rezultat suradnje institucija BOKU-Met (Institute of Meteorology of the University of Natural Resources and Life Sciences), ARSC (Arctic Region Supercomputing Center) i IMG (Institute of Meteorology and Geophysics of the University of Innsbruck) te entuzijazma znanstvene zajednice. Ciljevi HiRCoT-a bili su: 1) identificirati probleme pri numeričkom modeliranju sa razlučivosti ispod 1 km u kompleksnom terenu tj. razumjeti ključna područja modelskih nepouzdanosti i formulirati glavna pitanja vezana za njih; 2) Skicirati mogućnosti kako pristupiti tim problemima. 3) Omogućiti istraživačima diskusiju ove problematike na zajedničkoj platformi (online kroz wiki stranicu i osobno). Ovo prethodno priopćenje će iznijeti pregled tema i istraživačkih prioriteta diskutiranih na radionici.

Ključne riječi: Atmosfersko modeliranje visoke razlučivosti, fizikalne parametrizacije, numeričke sheme, ulazni podaci i inicijalizacija, računalni aspekti, HiRCoT radionica

BACKGROUND AND CONCEPTION OF HiRCoT

Local and regional weather and climate is strongly influenced by topography and land-use features at the respective scales. While the climate modeling community is performing runs typically at resolutions of 100, 50 km or, at most, 10 km, higher resolutions are needed for places with complex topography (eg., Szintai et al. 2010; Schicker and Seibert, 2009; Zängl, 2007) and dynamical downscaling seems the way to go. However, this path leads towards similar problems that the NWP and forecasting community are already facing. Whereas horizontal and vertical resolutions as high as possible would be preferable, several obstacles are encountered on the way. Even only from a practical perspective, the higher the resolution the larger, and not following a linear progression but exponential, the computational demands (Morton et al. 2010a,b). This is not a standalone need and requires the models to evolve in the same direction, being more scalable and even conceived and programmed with the end-user potential resources and requirements in mind, including, for instance, multi nested configurations with large domains and kilometer or sub-kilometer horizontal resolutions. Besides model scalability issues, also static and non-static input data require updates in space and time. Ingesting high-resolution topography, up-to-date land-uses, vegetation fraction and soil moisture and temperature are fundamental to make models perform realistically at high resolutions, with correct atmosphere-surface interaction. Once more this comes at a certain cost. For example, introducing the newest Digital Elevation Maps at resolutions of 3” to 1” to work with similar horizontal resolutions in the computational domains leads to problems in the numerical stability when very steep slopes are involved and with problems in the vertical formulations in the models. New numerical schemes then may come with the use of high-resolution input data and modeling. Having proper initial and boundary conditions is as well problematic. Even with the best elevation data-sets, land-uses and vegetation fractions, the semi-permanent variables such as soil moisture and temperatures are not well represented and have a profound influence on the local dynamics. Off-line models or certain pre-processing to spin-up the soil proprieties, or on-line models could be merged with the usual NWP models but this comes once more at a certain computational cost and adds up the intrinsic problems of such models. The same occurs with models themselves: NWP models were initially designed and tested for certain conditions, typically for relatively flat and homogeneous terrains and not for complex and inhomogeneous regions. When the resolution increases and we move to the km scale, those parameterizations that hold at coarse scales start being troublesome and may not hold any longer. Boundary layer parameterizations become critical at this point (~500 m) and new directions need to be taken, either by moving to three-dimensional LES schemes or by refining or developing new parameterizations.

The past few years have led us into this direction and it is time for the community to come together and look forward to the years to come in with a common ground and understanding of the underlying problems. With this idea in mind, HiRCoT (High Resolution modeling in Complex Terrain) was created.

HiRCoT is aimed at:

1. Identify the problems encountered when modeling at grid spacing lower than 1 km over complex terrain. This means, under-

standing the key areas that are troublesome and formulate the key questions about them.
2. Map out possibilities on how to address these issues.
3. Provide researchers with an inclusive forum to discuss and collaborate to solve targeted issues (online through a password-protected wikipage and face-to-face).

The inaugural 3-day workshop was held during 21-23 February 2012 at the Institute of Meteorology at the University of Natural Resources and Life Sciences of Vienna (BOKU-Met) and was organized by cooperation between the Arctic Region Supercomputing Center (ARSC, University of Alaska Fairbanks), the BOKU-Met and the Institute of Meteorology and Geophysics (IMG, University of Innsbruck). It was supported by the World Weather Research Programme, through its working group on Mesoscale Weather Forecast Research (WG MWFR) and brought together researchers from universities, research institutes, national meteorological services and high-performance computing (HPC) facilities. Of the more than 100 registered members of the HiRCoT wikipage, 33 scientists attended from 14 countries. The workshop was organized with participant contribution right from the start of the conception of the workshop via the wikipage created as well as by e-mail communication. For each of the four sessions briefly summarized below, namely Computational Aspects, Physical Parameterizations, Numerical Aspects and Input Aspects, selected participants presented the current state of the art modeling practices and techniques as well as the problems and challenges in each category. This material provided the basis for active discussions and debates during the sessions and helped wrapping up a board final plenary discussion.

THEMATIC AREAS

Physical Parametrisations

With respect to physical parameterizations high-resolution numerical modeling in complex terrain faces two general problems:

1. Complex topography would call for horizontal resolution on the order of a few hundred meters, what constitutes the 'terra incognita' according to Wyngaard (2004). In this range of scales RANS (Reynolds-averaged Navier-Stokes equation) models are no longer appropriate when approaching from the large-scale side (turbulence is [assumed to be] entirely sub-grid scale and hence fully parameterized). Large-Eddy Simulation (LES), on the other hand, requires even smaller grid sizes since it is based on filtering the momentum conservation equations in the inertial subrange of the turbulence spectrum. It was recognized that full prognostic three-dimensional TKE schemes including TKE advection might be an appropriate modeling choice for RANS models – thus assuming that at least for operational (NWP) modeling and many other applications, such as dynamical downscaling at sub-kilometer resolutions (e.g. Horvath et al., 2012), LES is not a realistic option at least for the next decade or so.
2. Due to the high spatial resolution, topography becomes steep in areas of complex terrain. Moreover, due to both thermal and dynamical processes the boundary layer is inherently (horizontally) inhomogeneous. Turbulence parameterizations, however, are based on available theory for horizontally homogeneous and flat (HHF) terrain (Rotach and Zardi, 2007; Baklanov et al., 2011) so that they cannot readily be used in highly complex terrain. An assessment of to what degree HHF-based similarity theory can actually be used in complex terrain is presently outstanding. The same is (consequently) true for a thorough investigation of the performance of presently available meso-scale models in highly complex terrain.

A number of specific problems that arise in complex terrain were furthermore discussed. These include:

- Atmospheric radiation: normal-to-surface orientation is relevant rather than vertical (as usually implicitly done in numerical models) and shadowing through surrounding topography (and self-shadowing) must be taken into account. Most radiation codes are one-dimensional which leads to problems in high-resolution simulations. Extensions to radiation codes have successfully been tested (e.g., Müller and Scherer, 2005).
- Semi-permanent surface characteristics: local, especially thermally driven flows prove highly sensitive to variables such as soil moisture, snow depth or albedo. For example, the one-dimensionality of the soil model

does not address the (potential) run-off from a slope site to a valley floor, snow is often present in (mountainous) complex terrain. Often an 'external simulation' (e.g. running an off-line hydrological run-off model to obtain soil moisture fields) seems to be successful (e.g. Chow et al., 2006).

- Surface wind biases. Hilltop locations and valleys often have a high-wind bias related to the sub-grid topography that provides an additional stress. Similar solutions as for large-scale models ('orographic drag parameterisation') seem to be promising (e.g. Jimenez and Dudhia, 2012).

In order to address all these issues, to derive and test new parameterizations for numerical models in highly complex terrain there is a need for reference data. From earlier projects (e.g. MAP Riviera, Rotach et al., 2004) usually only a limited number of episodes (typically a number of 'golden days') are available, which lack generality and abundance. Also, 'complete' observations are almost impossible to achieve due to spatial inhomogeneity. Therefore an integrated approach should be adopted, which combines detailed measurements at characteristic sites with high-resolution numerical modeling (below the 'terra incognita' resolution, using LES closure). Measurements will have to include both the mean flow and turbulence characteristics in 3d in order to validate the LES. When the 'right flow for the right reason' can be reproduced (i.e., both mean flow and forcing characteristics such as surface friction and radiation are within defined limits of the observations) model variables can complement the necessarily incomplete measurements, providing a true testbed to assess the performance of RANS models. This approach comes close to what has been proposed by the World Weather Research Programme's working group on Mesoscale Weather Forecast Research (WG MWFR) as Integrated Mesoscale Research Environment, IMRE (WWRP 2009). The Innsbruck Box (or i-Box, Stiperski et al., 2012) has been designed and is presently being realized in this spirit.

Numerical Aspects

The session on numerical aspects dealt with some of the wide range of numerical issues meso-scale meteorological models are known to have. Four sub-topics were addressed:

1. **Accuracy**. In theory, when numerically solving differential equations one should aim at higher-order accuracy. In complex terrain and with high resolution, however, input data often have a native resolution that is too coarse to accurately represent the small-scale atmospheric variability. Hence, higher-order accuracy is likely not to be beneficial (Janjic et al., 2011). Approaches that go beyond formal accuracy can be advantageous and very cost effective, such as the advection scheme of Janjic that also considers diagonal directions.
2. **Stability**. The explicit marching schemes adopted in NWP models are subject to numerical stability criteria. A typical example is the CFL (Courant-Friedrichs-Lewy) condition. Another example is the stability constraint introduced by the finite-difference discretization of the diffusion terms in the governing equations, particularly when the metric terms from the coordinate transformation are taken into account. Implicit schemes generally have better stability properties compared to explicit schemes. However they tend to be less accurate. More importantly, implicit schemes are non-local, which are not favorable for parallelization. The commonly used off-centering techniques can increase stability, but also have dissipative properties. Practical workarounds to cope with numerical stability problems include the use of an adaptive time-step or the use of w-damping. The latter solution is however unphysical and therefore not recommended.
3. **Diffusion**. Excessive diffusion can destroy the benefits of high resolution resulting in very smooth fields. Explicit diffusion can be more easily controlled by the user, as it is added to the equations in the form of diffusion operators or divergence damping. In complex terrain, explicit horizontal diffusion should either be turned off or be done on the true horizontal direction. Implicit diffusion results from the numerical schemes and is more difficult to control, but has the advantage that it does not introduce systematic errors in mountainous terrain under weak-wind conditions.
4. **Coordinates**. In order to account for the surface topography, NWP models generally adopt a curvilinear terrain-following coordinate system. There is the problem of com-

puting the horizontal pressure gradient as a small difference of two large terms, which becomes inaccurate on steep slopes. Thus, models designed for application to higher resolution over complex terrain should possibly move to other coordinate systems in the future. A height-based Cartesian coordinates system (Steppler et al., 2002) is one of the most promising choices for high-resolution atmospheric modeling over complex terrain. However, this still needs further development, especially on how to avoid the small cell / cut cell problems (Walko and Avissar, 2008a, 2008b, Lundquist et al., 2010 and 2012, Yamazaki and Satomura 2010, 2012).

Input and Initialization Aspects

Within this area the following sub-topics were discussed:

1. **Land surface datasets** - Land surface characteristics include topography, water bodies, soil characteristics, land cover (LC), vegetation characteristics, and urbanized locations. Regarding topography, most models use the 1 km resolution GTOPO30, Global 30 Arc-Second Elevation product (USGS), which is insufficient to resolve sub-km scale features. Higher-resolution data sets (3” or 1”) are nowadays available but their ingestion is not always straightforward. Default LC data are usually from the early 1990s and based on a rather small number of different LC classes, not representing, for example, different kinds of urban structure. Newer LC datasets such as the European explain acronym (CORINE) data (100 m resolution, 44 categories) are more appropriate for sub-1 km studies. However, further information is required as most LC data are a set of assiged parameters estimated from coarse (> 1 km) measurements, such as roughness length, albedo, LAI, and vegetation fraction, to each grid point. Soil texture used in the models is typically based on the Food and Agriculture Organization of the United Nations soil type classification (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009); obtaining data with higher resolution is not easy. Soil texture is an important parameter as it determines the thermal and hydrological properties of the soil and it has a large influence on runoff.
2. **Land surface initialization and assimilation** – The land surface is usually initialized with data from forecast or global/regional climate models. Recent studies have shown that assimilation of soil moisture (satellite and station data) and lower surface observations (2 m temperature, humidity and wind) can improve simulation results (Dharssi et al., 2010, 2011; Han et al., 2012; Draper et al., 2011). High station density is needed for high-resolution assimilation. While feasible for single case studies, assimilation is not an option for climate projections. One way of initializing climate simulations is to use long spin-up periods. Another possibility is to use off-line land surface models, but they also require high-resolution gridded input data, which is difficult to obtain over complex terrain.
3. **Atmospheric initialization and assimilation** - Usually, a global (synoptic-scale) operational model provides initial and boundary conditions to be downscaled to the grid of the mesoscale model. Two components have to be taken into account: the temporal and spatial component. The temporal component is defined by the time resolution of coupling/boundary conditions (often 3-hourly intervals). Infrequent coupling will effectively filter out any high-frequency forcing component. For small-scale features or fast moving systems, it is necessary to decrease this coupling time, which implies much higher I/O for the model run. For the spatial component, it is important that the lateral boundaries are sufficiently far away from the area of interest, such that the lateral buffer zone is sufficiently wide and that strong forcing (or noise) at the lateral boundaries is avoided. Another area in need of model improvement is related to the vertical extrapolation and interpolation between the nests. Currently climatological temperature gradients are used which can result in large errors in steep terrain, especially for cold air pool events, which greatly depart from climatological means. Regarding assimilation, conventional data density is currently rather poor for very high resolution modeling. The use of non-conventional data sources like radar (with a typical grid size of 1 km) and GPS (as supporting source for radio soundings) is crucial. But not all data sources are equally important for the forecast quality.

Tests with AROME-France Convective-Scale Operationel Model have shown that surface observations, aircraft and RADAR data have the largest positive impact. For small-scale features, radar seems to be the most important data source (Brousseau and Auger, 2012). Due to increasing computer power, 3D-FGAT (First Guess at Appropriate Time), 4DVAR (e.g. Huang et al., 2009 for WRF) and EnKF (e.g. Caya et.al., 2005) are nowadays used for LAM.

Computational Aspects

The session on computational aspects was brief, due to the background of most of the attendees of the workshop. Three main topics were discussed

1. **Computational resources** - The greater demand for computational resources is inherent with the increase in model resolution. This was exemplified by real-world cases with the need of very high resolutions for a number of meteorological processes that simply failed to be captured by the numerical models until 1 km and finer horizontal resolutions were approached (Stevens et al. 2010, Morton and Mölders 2010).
2. **Input/Output (I/O) paradigms** - Several studies (e.g., Arnold et al., 2011) have demonstrated that distribution of I/O operations to different CPUs is a key issue in high-resolution atmospheric modeling and when ignored, often constitute one of the main bottlenecks. A typical parallel implementation of WRF, the Weather Research and Forecast Model (Skamarock et al., 2008), for instance, will use the master/slave paradigm in which a single master task performs all of the I/O operations. In addition to being responsible for its own subdomain computations, the master task will read grid input data from files, distribute the subdomains to the slaves (including itself) and then as slaves compute results, it collects these and performs the necessary output operations on behalf of all the tasks. Alternatives include the direct I/O paradigm, in which each task performs its own I/O on its own locally-stored files. However, this presents a number of restrictions that make its use somewhat inflexible and constrained. A more intermediate approach utilizes pnetCDF (parallel netCDF), whereby I/O operations are performed through a specially compiled parallel library, allowing tasks to read/write from single shared files. This, however, still falls far short of the direct I/O approach. A more promising approach is a combination of pnetCDF and quilting (with asynchronous writing), in which several tasks are assigned to act as I/O condensers, thus serving as master tasks in the master/slave paradigm.
3. **Benchmarks** - Benchmarks should be model-specific and comprehensive and include compiler options and architecture. It was agreed, however, that these simulations should be long enough to include all the processes in typical model runs. In addition to measuring performance, these benchmarks should also evaluate the quality of the model results since compiler options and rounding errors may affect the model outcome. Finally, the benchmarks should be adapted to the end-user's needs, since the weather forecasting community may not have the same motivations as the climate modeling community, even when they both deal with the same areas of complex topography.

OVERVIEW AND OUTLOOK

Four thematic areas were discussed in the HiRCoT workshop and the main questions appearing in simulations at high resolutions in places of complex topography were identified. HiRCoT aimed at understanding "which problems we have" in order to aid the decision "which direction shall we take and what problems should be first addressed" and thus serves as a starting point for the development of a roadmap to improve high-resolution modeling. HiRCoT began strongly in February 2012, leading to the creation of a detailed report (see the final report, Arnold et al., 2012) and the participants actively supported furthering the initiative by suggesting a follow-up workshop with a time horizon of two to three years.

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