High Resolution Modelling in Complex Terrain. Report on the HiRCoT 2012 Workshop, Vienna, 21–23 February 2012

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Abstract

During the past years the modelling community, both from the application and pure research perspectives, has been facing the challenge of high-resolution modelling in places with complex topography. In February 2012, as a result of the collaborative efforts of BOKU-Met, ARSC, IMG and the enthusiasm of the scientific community, the HiRCoT workshop was held in Vienna.

HiRCoT objectives were: 1) To identify the problems encountered in atmospheric modelling at grid spacings of 1 km or less over complex terrain. This means to understand the key areas that cause difficulties and to identify formulate the respective key issues. 2) To map out possibilities on how to address these issues. 3) To discuss the issues on a shared platform (online through a password-protected wiki, and face-to-face).

This document contains a summary of the thematic sessions with the topics on which the discussion was centred, and it is organised in the same manner as the workshop.

1 Introduction

1.1 Origins

The HiRCoT workshop was the result of a collaboration between the Institute of Meteorology (BOKU-Met) at the University of Natural Resources and Life Sciences (BOKU) in Vienna, Austria, and the Arctic Region Supercomputing Center at the University of Alaska Fairbanks (ARSC). In early January 2011, Dèlia Arnold (BOKU-Met) and Don Morton (ARSC) initiated an informal collaboration and soon had the vision of organising an international workshop dedicated to the promotion of joint research endeavours in high-resolution atmospheric modelling in complex terrain (HiRCoT). Irene Schicker and Petra Seibert, also from BOKU-Met, offered their support and ideas, and a proposal was submitted to the US National Science Foundation, defining a structure for the workshop and seeking funds for American participation. Although the proposal was not funded, the foundation for the workshop had been laid, and within these first months, ARSC and BOKU-Met colleagues refined the structure and began to promote their ideas more broadly. Subsequently, a third enthusiastic co-organiser, Mathias Rotach (Institute of Meteorology and Geophysics at the University of Innsbruck, Austria) joined the team. Through him, the workshop got connected to WMO's World Weather Research Program (WWRP), through its working group on Mesoscale Weather Forecast Research (WG MWFR).

The vision for this workshop was to conduct something unconventional, making it a true working meeting with full participation, as opposed to a more traditional workshop structure consisting of formal presentations where serious discussions would be deferred to the breaks. Rather, the vision was a truly interactive workshop where all participants should be active. The first step to implement this concept was to open a wiki system (DokuWiki) in July 2011, hosted at BOKU-Met, to enable – early on – the organisation of the workshop to be based on the interaction of the participants. In fact, a guiding principle of the workshop was that it belonged to and was influenced by all participants, not just the original organisers.

Through the coordinators, a community of interested participants was gathered, and the structure of the workshop was refined. Many of the workshop participants had been aware of the planning process for ten months and participated with their ideas, but it was not until January 2012 that the activity blossomed in the form of posts in the wiki, documents sent to the participants and the selection of people who would moderate the discussions and – the ones designated to trigger them – the *designated participants*.

The workshop took place from 21 to 23 February 2012 at the University of Natural Resources and Life Sciences in Vienna, with logistical support provided by BOKU-Met and WWRP. In total, 31 people attended (Figure 1), from Andorra, Argentina, Austria, Canada, Croatia, France, Germany, Italy, Japan, Nepal, Spain, Switzerland, United Kingdom and the United States. Several others who could not physically attend the workshop contributed significantly to the programme with their ideas.

Fig. 1: Group picture of HiRCoT participants on the roof of the BOKU building where the workshop was held.

1.2 Aims

HiRCoT was launched to address issues that appear in atmospheric modelling over complex (mountainous) terrain under high resolution. We did not strictly define "high resolution", but, it may be understood as resolution that goes beyond the original design of model developers or well-established trouble-free applications. In practice, we were focussing often on grid spacings of about 1 km. The workshop did not focus on specific models, since limitations and problems as well as virtues and advantages are similar for the various models.

The overall goals of the workshop were, therefore:

- To **identify the problems**.
- To **map out possibilities** on how to address these issues.
- To provide a platform for **discussion** (**online and face-to-face**).
- To provide an opportunity to promote **collaboration** and the development of joint projects.
- To possibly form the starting point for a **series of workshops.**

1.3 Structure

The three-day HiRCoT workshop included sessions on four thematic areas and a final discussion[1]. These thematic areas were

- Computational issues
- Numerical issues
- Boundary Layer parameterisations
- Initialisation and input data

For each of the four sessions devoted to thematic areas, three key roles had been defined:

[1] http://met.boku.ac.at/hircotwiki/doku.php?id=workshop_info-:agenda

- **Designated participant**: This HiRCoT participant prepared and presented an *input statement* gathering the key issues and hot topics in the thematic area in collaboration with all the other participants. Each session was opened by this *input statement*, supported by a set of slides to trigger interaction and discussion.
- **Rapporteur**: The long discussion sessions, ranging from 2 to 5 hours, were not recorded but one participant acted as a rapporteur to keep the minutes of the key statements and conclusions in each session. Rapporteurs presented a summary in the final discussion.
- **Moderator**: Each discussion session had one moderator to organise the interaction of the participants and guide the discussions.

The final joint closing session was devoted to wrap up the reporting activities, to organise the post-workshop activities and decide about the future activities of the group.

The present report is largely based on contributions from designated participants and rapporteurs.

2 Thematic area 1: Computational issues

Discussion was mainly about sharing examples and experience about the issues modellers find when moving towards high resolutions in both research and operational applications, seeking to address the practical, computational problems. The team organised an overview of some of the primary computational issues that influence the quest for high-resolution modelling in complex terrain. The following points were addressed:

- Several examples of the real-world needs for very high resolution were presented. They illustrated how certain terrain-induced meteorological processes simply are not captured until 1 km and finer resolutions are used.
- The computational costs of refining resolution were addressed, with an example of transitioning from 9 km to 1 km resolution, in which case, from a theoretical analysis of the performance, it was determined that a forecast taking one hour at 9 km resolution would take well over a month at 1 km resolution.
- The high computational demands were discussed in the context of WRF benchmarking suites developed by Arnold and Morton, providing test cases which could be run and compared with others' results to start determining the resource needs.
- I/O performance issues were discussed, which are probably the limiting factors for modelling large domains at high resolution. The effects of I/O on the benchmarking cases were discussed.

2.1 Examples of real-world need for high-resolution in complex terrain

A demonstrative case of the value of high-resolution modelling was developed by Don Morton and Nicole Mölders at University of the Alaska Fairbanks (Morton and Molders 2007), investigating the ability of WRF to capture terrain-influenced wind events. Model domains were set up over Interior Alaska to simulate a typical wind event and how it manifests itself in the rugged area of the Alaska Range. Though the study was broad in scope, the particular case that stands out is the comparison of model wind forecasts with observations at Trims Camp (Alaska Department of Transportation met station).

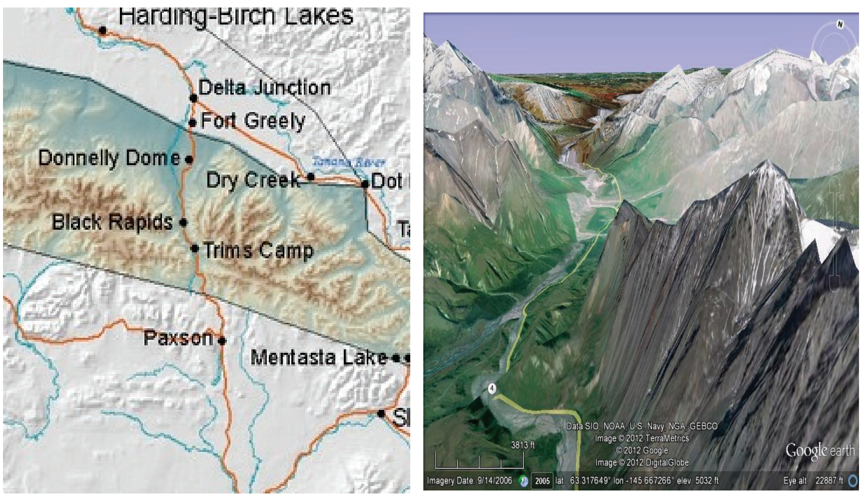

Fig. 2: Region of study by Morton and Molders (2007) (left), and an aerial view (© Google) of the topography (right).

The regional domains were set up at horizontal resolutions of 27, 9, 3 and 1 km. It is obvious from Figure 2 that at 27 km resolution the terrain is not at all captured, and is then progressively captured at finer resolutions down to 1 km.

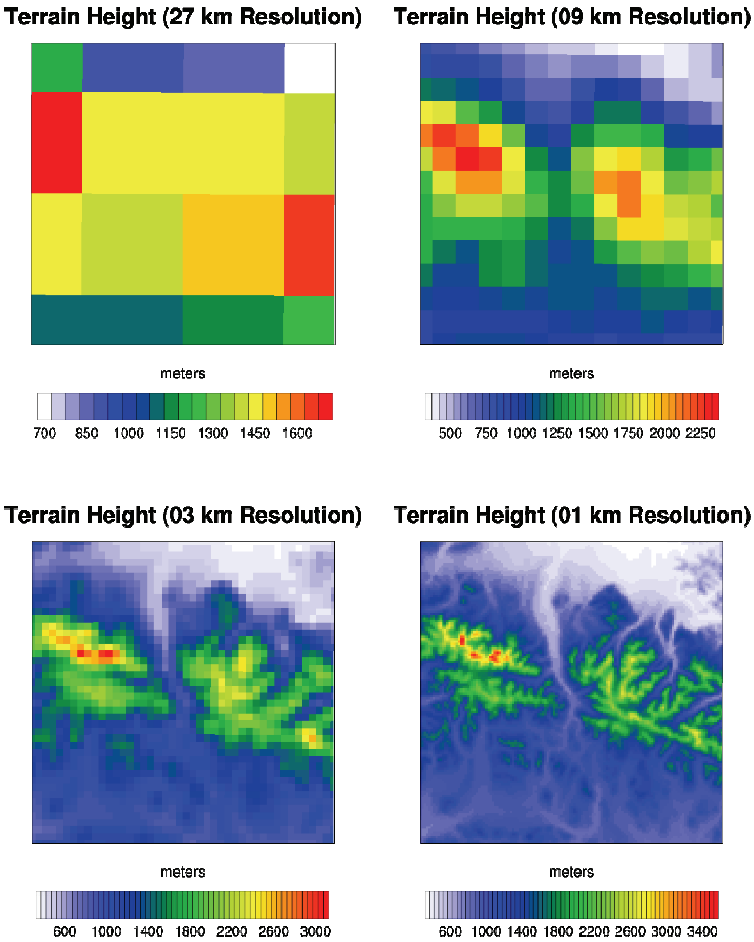

Fig. 3: Model topography with refined horizontal resolutions from 27 to 1 km.

Wind speed and direction model forecasts were compared against observations at Trims Camp (TRDA2). The key finding here was that at resolutions down to 3 km, model forecasts deviated substantially from the observations, but at 1 km resolution, all of a sudden the model forecast was in very close agreement with the observations.

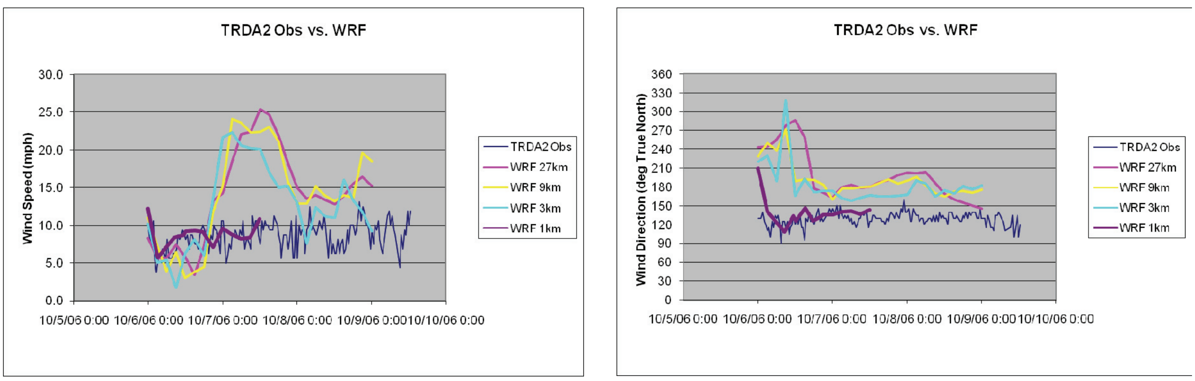

Fig. 4: Modelled versus observed time series of wind speed (left) and direction (right) at TRDA2 with the output of the several domains at varying resolutions (coloured lines).

Although it should be obvious that if you want to capture terrain-influenced events, you need to adequately resolve the terrain, this was an eye-opening, real-world finding, illustrating the fact that there are a number of cases in atmospheric modelling that simply cannot be addressed without committing to the computationally intensive resources needed for high-resolution modelling.

Another case presented was one of an anomalous wind event on an obscure, relatively non-complex terrain Saint Lawrence Island between Alaska and Russia (Stevens at al. 2010).

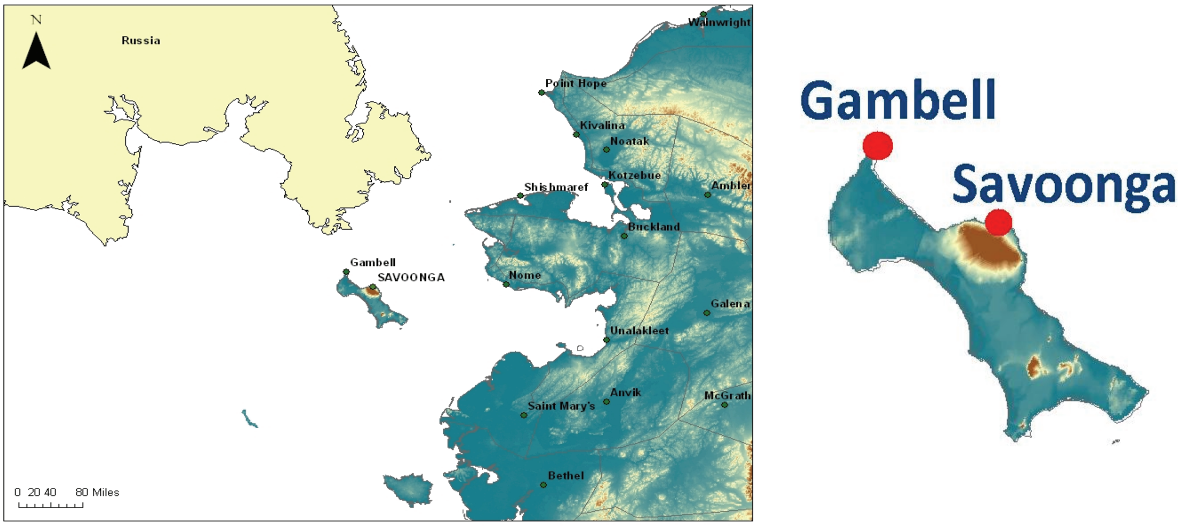

Fig. 5: Location of Saint Lawrence Island with respect to Russia and Alaska (left), detail of the island (right).

In this event, there was a large, not-uncommon low-pressure system to the southwest of Saint Lawrence Island, generating a strong and relatively smooth southerly wind flow towards the island. Forecasters at the time were more focused on winter storm issues on the mainland and were surprised the next day when Savoonga recorded an official peak wind of 44 ms^{-1} and an unofficial 62 ms^{-1}. Meanwhile, Gambell, about 64 km to the northwest, recorded a peak wind of only 27 ms^{-1}. Given the relatively smooth synoptic scenario over both locations, the question was posed about why the winds would have been so much stronger at Savoonga. The hypothesis introduced at the Fairbanks Forecast Office was that a small feature – coined a relative “pimple” – the 673 m MSL Atuk Mountain to the south of Savoonga was responsible for generating lee-side breaking mountain waves that generated the extreme winds. No such mechanism was available for Gambell, and high-resolution WRF simulations were conducted on this case study in an effort to determine whether this might be a viable hypothesis. High-resolution simulations of 1 km – fine enough to somewhat resolve Atuk Mountain – were performed and simulation results suggested that, indeed, the relative “pimple” on the landscape had the potential to induce the severe winds at Savoonga (Figure 6).

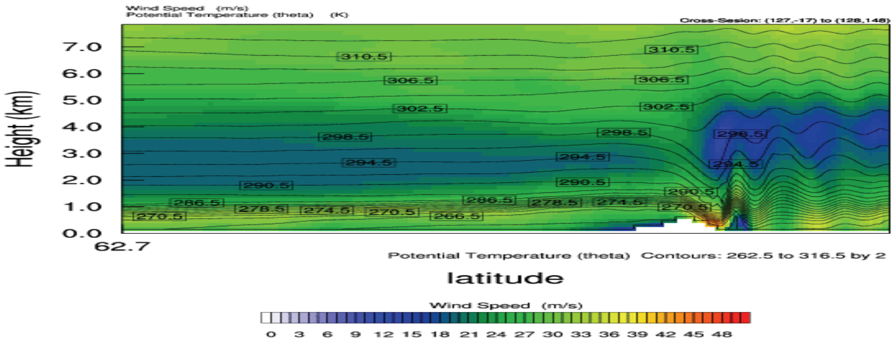

Fig. 6: Modelled winds of up to 40 ms^{-1} breaking down on Savoonga.

This was yet another example demonstrating the need for high-resolution modelling in smooth, yet complex, terrain for real-time operational purposes. Standard operational models did not resolve Atuk Mountain and couldn't possibly anticipate such a small-scale but significant feature.

After presentation of these "motivational" cases, the topic then turned to the computational costs of these high-resolution simulations (Morton et al. 2009, 2010a, 2010b, 2012c). In one example, the region around Fairbanks, Alaska, was displayed (Figure 7) and it was emphasised that a simple transition from 9 to 3 km resolution would result in a 9-fold increase in number of horizontal grid points and a 3-fold increase in the number of time steps. In other words, in a best-case scenario, a forecast that might have taken one hour at 9 km would take over a day at 3 km resolution. Taking this a step further and considering a refinement from 9 to 1 km resolution would result, in a best case scenario, a forecast

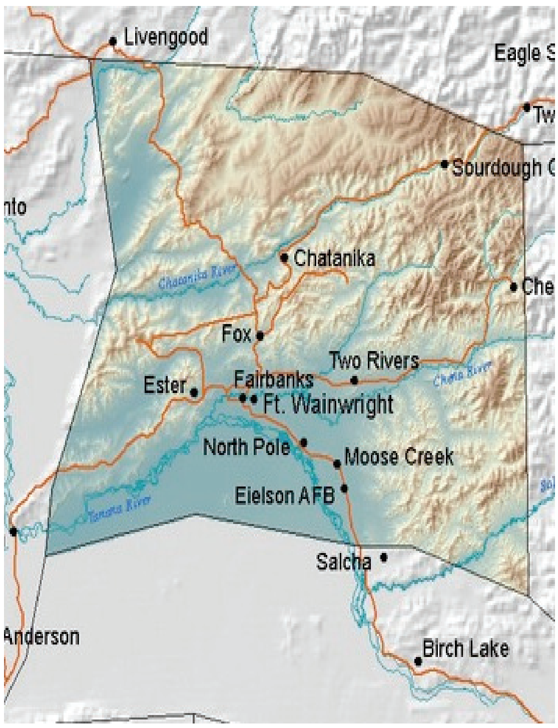

Fig. 7: Location of the domain of study to evaluate increase of computational resources with increasing resolution.

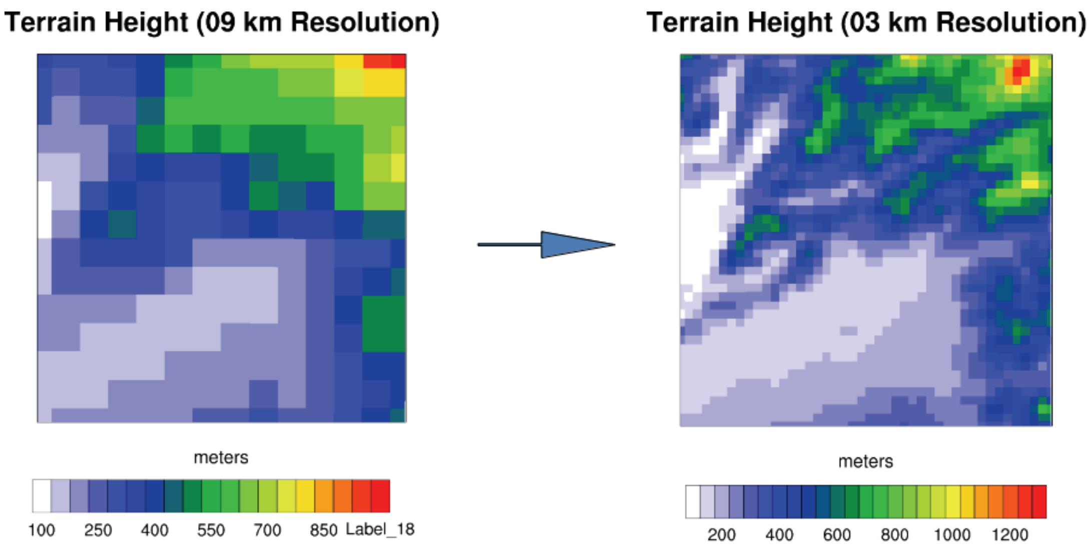

Fig. 8: Refinement of 9 to 3 km resolution. Changes in topography as seen by WRF.

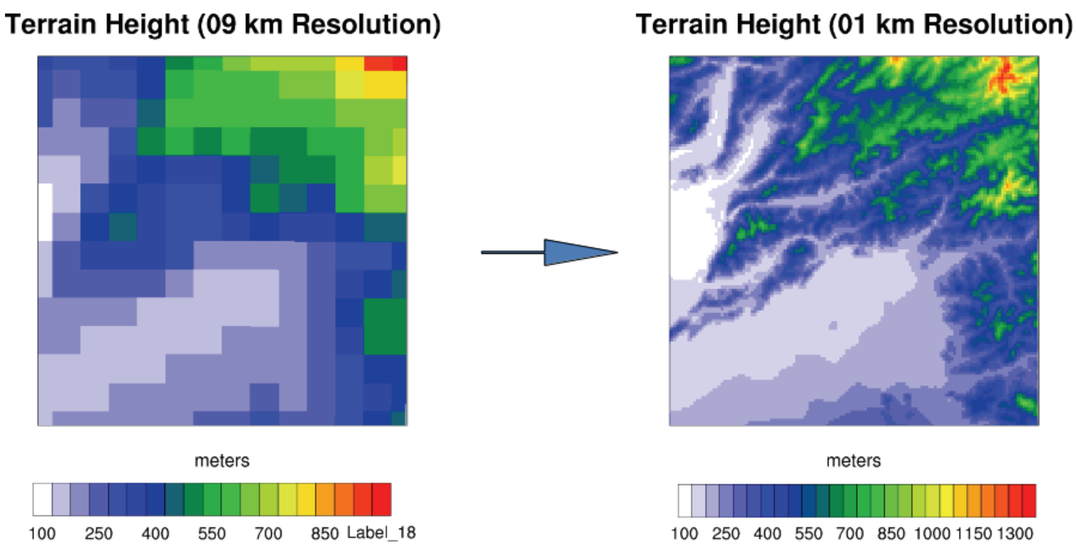

Fig. 9: Refinement of 9 to 1 km horizontal resolution. Changes in topography as seen by WRF.

that took one hour at 9 km resolution would take a month at 1 km resolution (assuming constant computational resources). In addition to the raw computational costs, the costs and associated complexities of storage would increase by orders of magnitude. These examples were presented to illustrate the dire need for high performance computing resources in any kind of a high-resolution production environment.

With experience in pushing weather models to billions of grid points, the presentation then addressed the very real concerns of I/O limitations in a high-performance computing (HPC) environment. A typical parallel implementation of WRF will use the master/slave paradigm in which a single master task performs all of the input/output operations. In addition to being responsible for its own subdomain computations, the master task will read grid input data from files, distribute (scatter) the subdomains to the slaves (including itself) and then as slaves (including itself) produce results, the master gathers these and performs the necessary output operations on behalf of all the tasks. In addition to posing a significant bottleneck, the added responsibility of the master task significantly adds to its memory requirements. As a result, while all but the master task often operates well within memory limitations, the added responsibility of the master task to scatter / gather data can easily result in it exceeding memory capacity, causing the entire simulation to fail. In the following academic example (Figure 10), a naïve domain decomposition of 448 million grid points results in a per task memory requirement of 1.9 Gigabytes. However, Task 0 (the master) requires an additional 1.8 Gigabytes for reading global fields and scattering to slave tasks, and then gathering the fields to subsequently perform output operations. Hence, the additional work required by Task 0, in this scenario, kills the entire simulation.

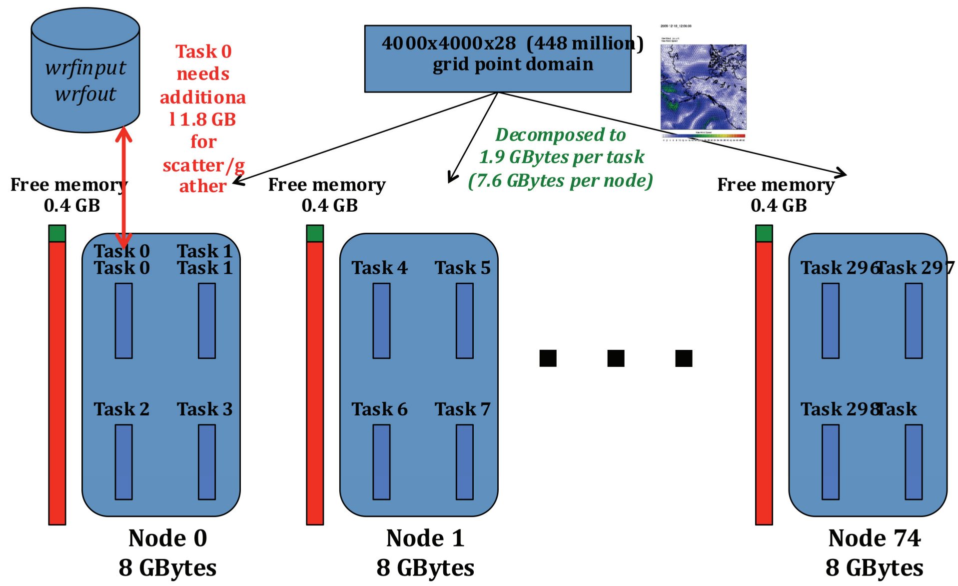

Fig. 10: Default master/slave task distribution, failing under high memory loads.

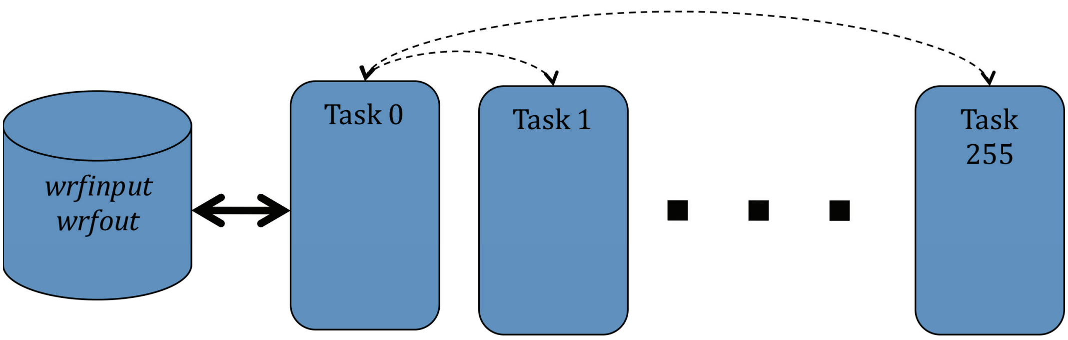

Fig. 11: Typical master/slave I/O paradigm with Task 0 acting as master.

With this introductory example of default scatter/gather operations, which works quite well in non-demanding environments, the stage was set to address more effective, alternative I/O paradigms. The direct I/O paradigm (Figure 11), in which each task performs its own I/O on its own locally stored files, is supported by WRF and offers the most efficient approach. However, it presents a number of restrictions that makes its use somewhat inflexible and constrained. For example, if the WRF input files have been generated under this paradigm using P tasks (and therefore P files), the WRF simulation itself must take place with P tasks. Furthermore, with this paradigm, output files are written out in subdomains and require special processing (to the best of our knowledge, this isn't even available).

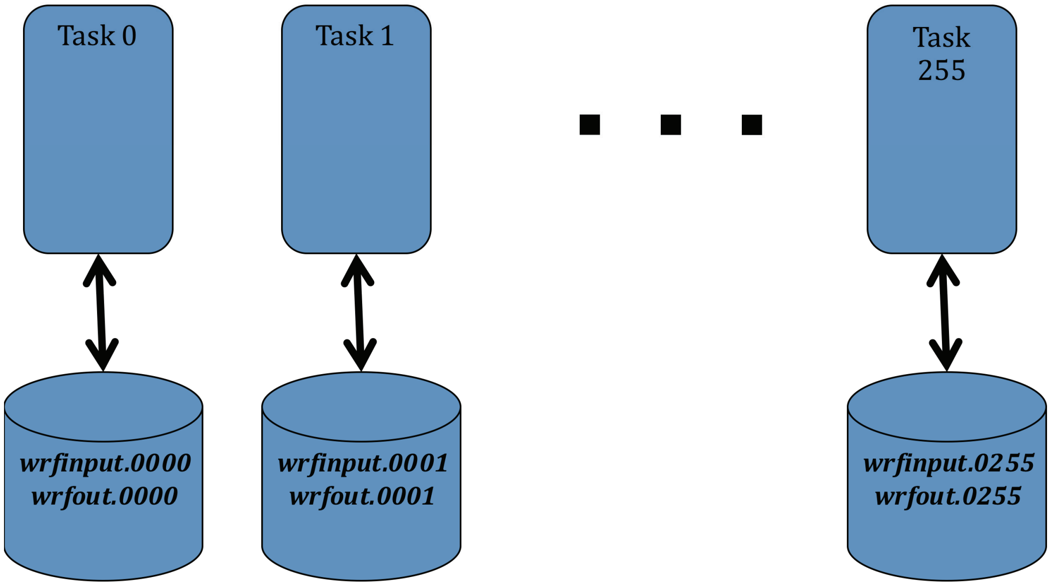

Fig. 12: Direct I/O paradigm.

A more intermediate approach utilises pnetCDF, whereby input/output operations are performed through a specially compiled parallel library, allowing tasks to read/write from single shared files. Although the performance here is much better than the master/slave operations, it still falls far short of the direct I/O approach described above.

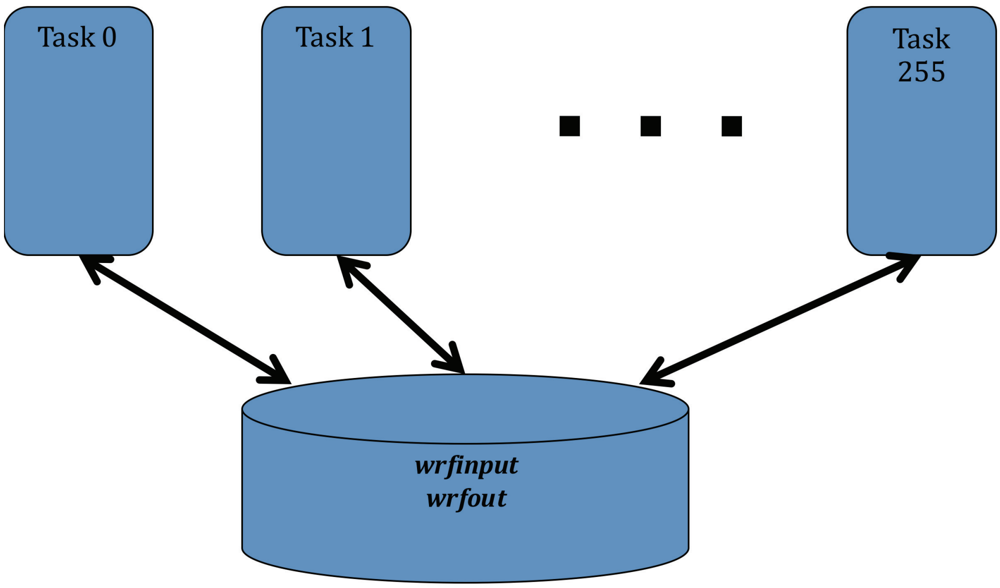

Fig. 13: I/O operations using parallel netCDF.

Finally, WRF implemented the concept of asynchronous I/O whereby non-compute tasks were dedicated solely to perform disc read/write operations. A typical output operation, therefore, would have compute tasks sending data to dedicated I/O servers, rather than the master Task 0, and then these I/O servers would perform the write operations, asynchronously, while the compute nodes were proceeding with the next round of computations (Porter, 2010).

To wrap up the session, participants had been encouraged to present their own concerns and experiences in computational issues, and these were addressed during the session. The participants' input was diverse, and a few of the key points (that aren't addressed elsewhere in this document) are outlined here:

– From a research perspective (as opposed to operational), access to HPC resources is often not as critical as model design issues. Researchers can often afford to wait for completion of runs, so performance enhancement of codes may be unnecessary in such cases.
– Concern was expressed about the numerous compiler and hardware configuration options and how all of these may lead to different – sometimes incorrect - model outputs and performance.
– One participant expressed interest in discussing the merits of structured and unstructured grids in the context of scalability and overall computational performance.

2.2 Summary of discussion

The session triggered discussions and contributions from participants. For example, G. Zängl from DWD presented the performance of the ICON model. Whereas computational issues were identified as a crucial aspect, no general agreement on how to tackle the problems was reached. The models scale relatively well for current needs. However, all the HiRCoT participants agreed that in the future we may encounter several bottlenecks. To address this, we will need to reprogram models from scratch with scalability as one of the main aims and considering the possible architectures (new IBM Power chips, GPUs, etc) as well as including – as much as possible – tools such as pnetcdf and asynchronous I/O operations. Post-processing is as well a problematic issue since the model not only needs to produce output, but this very same output needs to be post-processed in an efficient manner, using similar parallel tools. Additionally, benchmarks and community needs were discussed.

Benchmarks should consider:

– Long benchmark periods instead of the typical 1 to 10 minutes in order to include all processes that may potentially affect the performance.
– The numerical output needs to be investigated in the benchmarks. Compilers, compiler options and hardware with its system software may influence the model outcome. For instance, the rounding errors may become tricky. However, it is difficult to find funding for this kind of task. Some efforts, though, have been made in this direction (Langkamp, 2011).
– Benchmarks should be created according to the user needs. The climate modelling and weather forecasting communities have different needs although they both need to deal with high-resolution modelling in complex terrain.
– Whereas all participants agreed that it would be good to provide, outside of the benchmarks, some standard model configurations to the user community, this was deemed unfeasible to achieve or should, at least, be model specific.

2.3 Resources

The interest in computational demands of high-resolution models led to a BOKU-directed project (Arnold, 2011) where costs of real-world simulations, using WRF models in a dynamic downscaling context were evaluated. A series of benchmark studies was initiated (Morton,

2011) to begin understanding what we can realistically expect from large, high-resolution simulations. These studies have led to the "User-Oriented WRF Benchmarking Collection"[2].

[2] http://weather.arsc.edu/WRFBenchmarking/

3 Thematic area 2: Numerical issues

The numerical issues discussed include the choice of the discretisation scheme with regard to accuracy, stability and computational cost as well as the impacts of implicit and explicit diffusion and problems associated with coordinate systems. While problems of high resolution and complex topography seem very apparent and relevant to the discussion, it has to be noted that the synoptic scale properties of a model should not be forgotten. Conservation of enstrophy (vorticity) is important for synoptic scale flows and governing the dynamics, as the success of the earliest numerical weather prediction (NWP) simulations proves.

3.1 Background

The successful use of mesoscale meteorological models crucially depends on the knowledge of technical aspects of the numerical methods they employ. The great majority of limited-area NWP models still rely on finite-difference discretisation methods, i.e., partial derivatives in the governing equations are replaced by ratios of finite space and time differences. The time integration is generally explicit, i.e., finite differences are forward-in-time. Among the most crucial issues are the numerical stability requirements (such as the Courant-Friedrichs-Lewy , CFL, criterion), which are based on a combination of horizontal and temporal resolution. For small grid sizes, these requirements may demand short time steps down to a prohibitive length, sometimes fractions of a second, which may be unfeasible, especially for real-time operations. Off-centering the integration time scheme to an implicit scheme offers more stability regardless of the Courant number, but renders the numerics much more complicated and – in the case of a horizontally implicit scheme – entails the need of solving an elliptic equation, which is challenging to parallelise on massively parallel architectures. Longer time steps will usually also entail larger discretisation errors.

Numerical noise occurs because of the nonlinear steepening of wave disturbances or because of nonlinear aliasing. Over complex terrain, it may be further enhanced if the orography forces short wavelengths, which challenges the accuracy of the advection and the pressure-gradient discretisation, and also the consistency of the metric terms. To some extent, filtering the model orography can cure deficits of the numerical implementation, but it is in general not desirable to run a model at high resolution in mountainous terrain and then lose a substantial part of the effective resolution due to excessive orography smoothing.

The major scientific challenge in this area is to understand whether finite difference (FD) schemes should (and can) be replaced by other more general schemes (e.g., finite volume, FV, Immersed Boundary Method, IBM, Ye at al. 1999, Calhoun et al. 2000, Mittal and Iaccarino, 2003, Tseng et al. 2003) that alleviate numerical issues with the sloping coordinate, but add issues related to the surface intersecting the model levels, and handling partially filled grid cells. Finite element schemes (FE, Mailhot and Benoit, 1982; Durran 2010) have their own problems, particularly in advection of sharp gradients. In these cases, FD methods can actually be more stable, though more diffusive.

3.2 Discussion on issues specific to high resolution and complex terrain

3.2.1 Accuracy

Countless methods for the numerical solution of differential equations exist, with different orders of accuracy. Higher-order accuracy generally means higher computational costs. What is normally meant by “accuracy” is the order by which the local truncation errors introduced by a numerical method decreases with decreasing space and time increments. Therefore, formal accuracy is essentially a quantification of how well discrete approximations fit to the continuous equations.

In real world applications, especially in complex terrain and with high resolution, the data used to specify the initial and boundary conditions often have a native resolution which is too coarse to accurately represent the small-scale atmospheric variability in complex terrain. In these conditions, however high the formal accuracy of a numerical scheme, model errors would be dominated by inaccuracies in the initial and boundary data. Higher-order accuracy is therefore not likely to be beneficial (Janjic et al. 2001). Ideas beyond formal accuracy can be beneficial and provide very cost effective methods, e.g. the advection scheme of Janjic that considers also diagonal directions.

3.2.2 Stability

As mentioned above, the explicit marching schemes adopted in NWP models are subject to numerical stability criteria.

A typical example is the CFL condition, which applies to the advection part of the governing equations: $c\Delta t/\Delta x<\beta$, where c is the physical propagation speed of a signal and β a coefficient depending on the discretisation. Another example is the stability constraint introduced by the finite-difference discretisation of the diffusion part of the governing equations, particularly when the metric terms from the coordinate transformation are taken into account: $M\Delta t/\Delta x^2<\beta$, where M is the physical diffusivity and β is again a coefficient depending on the discretisation. Note that, while the advection stability criterion is linear in Δx, the diffusion stability criterion is quadratic. As a consequence, Δt must decrease proportional to Δx^2 to maintain the integration of diffusion terms stable and only if the diffusivity is constant. That is, a 10-fold increase in horizontal resolution implies a 100-fold increase in time resolution. For typical parameterisation approaches, e.-g.- Smagorinsky diffusion, the diffusion coefficient has to scale with Δx^2.Therefore, the latter stability criterion is more likely violated at very high resolution and may cause a model integration to fail even if the (advective) CFL condition is apparently met.

Fully or partly implicit schemes generally have better stability properties compared to explicit schemes, and may even be unconditionally stable. However, even if more stable, they also tend to be less accurate. More importantly, implicit schemes are non-local, which is not favourable for parallelisation and generally limits their application to the vertical dimension. In fact, a common trick in numerical models is to introduce an implicit discretisation of the vertical gradients of pressure and vertical velocity, as well as of vertical diffusion terms. The trapezoidal discretisation of these terms can furthermore be “off-centered” or “forward-biased”. The commonly used off-centering techniques can increase stability, but also have dissipative properties adding to the implied dissipation of a numerical scheme.

Practical workarounds to cope with numerical stability problems include the use of an adaptive time-step (getting shorter if the CFL number is detected to exceed a threshold value) or the use of w-damping, i.e., locally reducing the vertical velocity component (which is often the most critical in high-resolution integrations over complex terrain) if instability in the vertical advection is detected. The latter solution is however unphysical and therefore not recommended.

3.2.3 Diffusion (explicit, implicit)

Artificial diffusion or artificial dissipation is the damping of disturbances over time as a consequence of the properties of the numerical method. Note that physical diffusion has a similar effect, i.e., it causes small-scale variability in a given field to smooth out over time. Artificial diffusion either is a property of the spatial differencing scheme (implied or implicit diffusion / dissipation), or it can be added explicitly as an extra term in the governing equations (explicit diffusion / dissipation). In both cases, it has no physical justification and is merely a numerical artefact. In other cases, and for some models which do not include a parameterisation for the physical horizontal diffusion, numerical diffusion is sometimes not only used for numerical stability, but also as a crude representation of the physical horizontal diffusion.

Since it is added to the equations in the form of diffusion operators, explicit diffusion can more easily be controlled by the user. The reduction of implied diffusion is a very complex task that can only be handled by the developers of the dynamical cores. For users it is generally beneficial to have dynamical cores with very little or no implied diffusion, so that they can control directly the explicit diffusion. As a rule of thumb, spatial schemes with odd-order accuracy (upstream biased) have more implied diffusion, while even-order schemes (centred) have less. Therefore, explicit artificial diffusion is generally added only when centred spatial schemes are used.

Artificial diffusion is useful as long as it helps to keep small-scale numerical noise under control. It is not difficult to get a model running at high resolution if there is enough diffusion, as the numerical problems are hidden by higher implied or explicit diffusion. However, diffusion can destroy the benefits of high resolution, resulting in very smooth fields, and, when applied to quantities with a strong vertical stratification (like temperature and moisture), induce large systematic errors over steep mountains if the metric terms have not been properly taken into account in the model. Note in addition that the effects of diffusion could look modest in some scalar fields, but could be severe in the vorticity that drives the large-scale dynamics. Explicit diffusion can, in principle, be controlled by the user as it is added to the equations in the form of diffusion operators or divergence damping. Hyperdiffusion operators (terms proportional to spatial derivatives higher than the second derivative) are more scale-selective, but have no physical justification. Divergence damping has the favourable property of not affecting vorticity of the geostrophic flow as well as having a physical justification.

In complex terrain, explicit horizontal diffusion should either be turned off or be done on the true horizontal direction and not along sigma coordinates (Zängl, 2002). 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.

3.2.4 Coordinates

In order to account for the surface topography, NWP models generally adopt a curvilinear terrain-following coordinate system. This design choice implies that the governing equations need to be converted from the “natural” orthogonal Cartesian formulation. The coordinate transformation causes metric terms to appear in the equations.

A full tensor-analysis-based change of a coordinate system, which is required to conserve the physical conservation properties as in the Cartesian coordinate system, leads to a fairly complicated form of the metric terms. It is however adopted in some models that employ a height-based terrain-following coordinate (such as ARPS and RAMS). In a model with a mass-based terrain-following coordinate, mass is conserved by definition. As a consequence, simpler coordinate transformations using the hydrostatic approximation for pressure can be used (Laprise, 1992).

In sigma coordinates (Figure 14 upper panel) one is left with the problem of computing the horizontal pressure gradient as a small difference of two large terms, which may become inaccurate on steep slopes, especially when the vertical resolution is very high. A commonly used rule of thumb is to specify a resolution such that the vertical spacing is not much smaller than the ground elevation increment across a horizontal grid element. Problems related to the incorrect computation of horizontal pressure gradients may be alleviated by formulating a prognostic equation for the perturbation pressure (with reference to a hydrostatically balanced reference state), rather than for the full pressure.

Many methods for dealing with the coordinate problem have been published in the past decades.

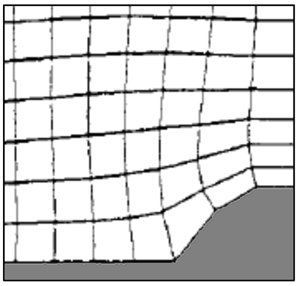

Fig. 4: Computer generated general curvilinear coordinates (Satomura 1989).

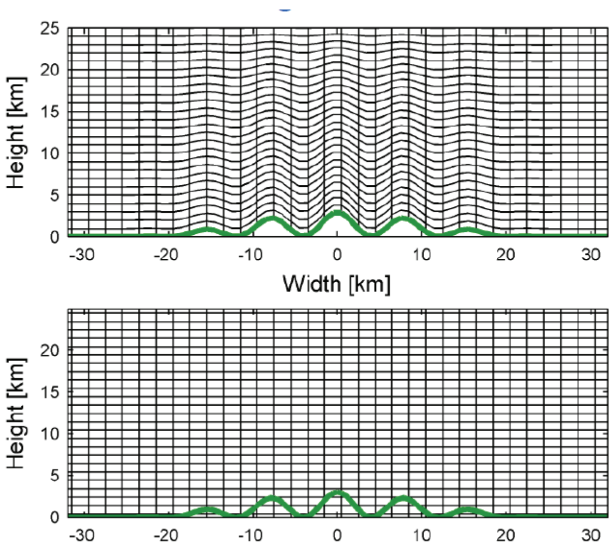

Fig. 5: Comparison of the usual sigma coordinates (above) and the immersed boundary method (below), from Lundquist et al 2008).

It is clear that the key limitation for terrain-following coordinate systems is high resolution over complex terrain with very steep slopes. Thus, models designed for this specialised application would possibly have to move to other coordinate systems in the future. Coordinate systems used in models are

– terrain-following pressure ("sigma", Figure 15) or height coordinates,
– boundary-fitting curvilinear (Figure 14), or
– Cartesian height (e.g., "immersed boundary method", IBM, Figure 15).

. Among these options, a height-based Cartesian coordinates system appears to be an attractive choice, due to the simple form that the governing equations assume. However, handling computational cells completely or partially filled by the topography is not a trivial task. In the Cartesian coordinates systems, there still exist several choices depending on how to avoid the small cell problem: an immersed boundary method (IBM, e.g., Walko et al., 2008), a cut cell (Figure 16) model with a thin-wall approximation (e.g., Steppeler et al., 2002), or a cut cell model with a cell merging method (Yamazaki and Satomura 2010, 2012, Figure 17). We are worried that the immersed boundary method and the cut cell model with the thin-wall approximation possibly obscure the lower boundary of the model (the position and the shape of the terrain). This type of coordinate system can also make only limited use of non-uniform vertical grid resolution.

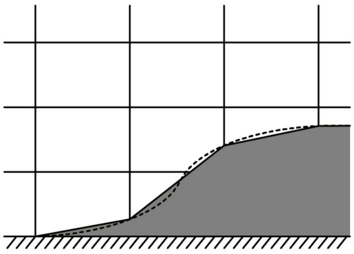

Fig. 14: Cut cell coordinates (Yamazaki and Satomura 2008).

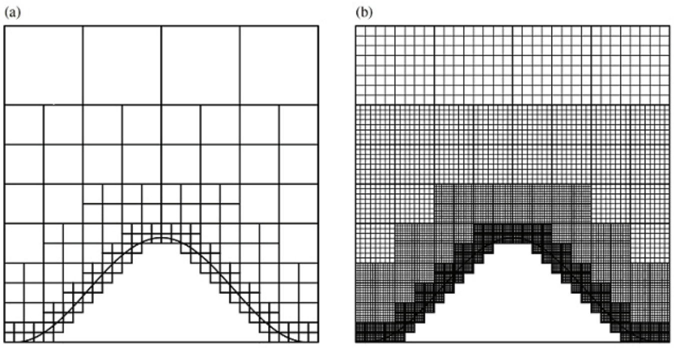

Fig. 15: Schematic of blocked structured cell system in cut cell methods. (a) Cubes and (b) cells around a cosine-shaped mountain for 2D computation. In this case, all cubes have 8 × 8 cells. (Yamazaki and Satomura 2012).

3.2.5 Benchmark strategy

Benchmarks are important to establish the accuracy of specific models under conditions of high resolution in complex terrain. We recommend setting up standard benchmarks, which should be used for the validation of new developments and prior to using any model not yet tested at high resolution. Starting with ideal cases of mountain waves is recommended because we can compare model results with analytical solutions. However, a comparison with results from linear theory only makes sense in very simple contexts, while it would not be meaningful in any case where non-linear effects are important (e.g., over very complex terrain). It is also recommended that not only the pattern of wind and temperature but also some second-order variables such as momentum flux should be compared, because these variables are sensitive to the small phase and amplitude errors. The model comparison results by Satomura et al. (2003) are an example of such ideal cases.

Other benchmarks include a) real cases where intense three-dimensional observations are conducted and high-resolution observational data are available, such as PYREX, MAP and others, which could be used to evaluate high-resolution models; b) long-time integration of real cases for statistical checks; c) in addition to the mean flow fields, the second moments (fluxes) and radiation etc (i.e. those variables representing the forcing of the boundary layer flow) should be included in the benchmark, so that the right flow for the right reason is being checked.

4 Thematic area 3: Boundary layer parameterisations

4.1 Background

Boundary layer and surface exchange parameterisations are usually based on knowledge of atmospheric turbulence from relatively homogeneous, flat terrain (e.g., similarity theory, see e.g. Stull 1988) and under optimal circumstances, i.e. near-steady-state conditions with neutral or weakly stable or unstable stratification ("HHF", i.e. horizontally homogenous and flat conditions). These are not the conditions we encounter in places with complex topography. There may be very heterogeneous land-use patterns, mountains with narrow valleys and steep slopes or at least hills, all of which lead to horizontally inhomogeneous PBLs (Rotach and Zardi 2007). Boundary layer parameterisations work fairly well down to km grid size. When the grid size becomes smaller, however, their applicability becomes questionable.

With respect to high-resolution numerical modelling, current meso-scale models use two different approaches to deal with turbulence:

In the *ensemble-averaging approach*, the Navier-Stokes equations are decomposed into mean and fluctuations (Reynolds decomposition) and subsequently ensemble-averaged. Turbulence is then fully parameterised, i.e., the variances and co-variances of turbulent quantities are expressed as functions of the mean flow variables (this will be called PBL parameterisation in the following). By definition, all model variables are mean (ensemble-averaged) fields.

In *Large Eddy Simulations (LES)* the Navier-Stokes equations are filtered with a filter length lying in the inertial sub-range of the turbulence spectra. Thus, the model resolves the large eddies (hence its name) and only small-scale turbulence, considered isotropic, is parameterised. Output fields from a LES are (in principle) instantaneous pertaining to a specific realisation of a random process. The realisation is usually determined by prescribed initial perturbations.

Interestingly, the resulting prognostic equations for the mean flow variables are formally identical for both approaches. The approaches differ with respect to the details of the turbulence closure models.

One of the issues of concern is that the usual, Reynolds-averaged turbulence schemes are one-dimensional, only considering vertical turbulent fluxes which are assumed to depend only on conditions in a single grid column, whereas turbulent structures in complex terrain are fully three-dimensional. Furthermore, when the grid cells become very small, horizontal turbulent fluxes as well as advection of turbulence, i.e. horizontal advection of turbulent kinetic energy (TKE), becomes more important. This is not implemented in most of the current mesoscale models. In addition, with smaller grid cells it becomes more and more questionable how much the mixing is already explicitly resolved by the model and what should still be parameterised. It must be kept in mind here that our knowledge concerning the turbulence structure in complex terrain (i.e., the characteristics that the numerical models should be able to reproduce) is very limited and thus further developments must go in parallel with observational efforts.

At the sub-km scale, some of the largest eddies, responsible for most of the production of TKE and of the fluxes of momentum and scalar quantities, start being resolved explicitly. We are then entering the realm of LES. However, LES has rarely been tested in complex terrain and also presents several open issues. Considering the usual approach of nested grids, which is mandatory in most of the real-world complex terrain applications for obtaining realistic boundary conditions, the innermost domain may be an LES domain which needs to be nested into a non-LES domain. This is not an easy task. Two-way nesting interaction becomes complicated through – among others – the following problems:

– noise produced at the nest boundaries,

– the spin-up needed for the LES domain to properly represent the turbulence.

– the size of the domains so that the borders are far enough from the region of interest

This of course makes this a hot topic in the modelling community.

4.2 Discussion

4.2.1 PBL vs. LES in real terrain

Wyngaard (2004) has introduced the notion of a so-called ‘terra incognita’ where the scale of the spatial grid is neither much larger than the scale of the large turbulent eddies (assumption of PBL parameterisations) nor much smaller (assumption of LES). Therefore, neither of the approaches is designed (or appropriate) for grid spacings corresponding to the 'terra incognita'. Current experience (Hong and Dudhia, 2012) suggests that PBL schemes may work well for grid spacing down to 300-500 m. On the other hand, LES grid resolution should be (much) less than 100 m in order to well resolve convective boundary layer eddies, and even smaller for the stable boundary layer. Therefore, the issue of 'terra incognita' may be most pronounced for grid resolution 100 m < Δx < 300 m. A thorough comparison between PBL and LES at these resolutions is still missing[3].

For PBL closures, the so-called ‘double counting’ problem has been raised, which states that the model parameterisation attempts to represent the entire turbulence spectrum (i.e., its energy), while at grid-resolutions smaller than about one km, turbulent motions are additionally partly resolved by the model dynamics. However, it can be argued that the issue of 'double-counting' may not be important since both explicitly resolved eddies and turbulence represented in the PBL scheme feed on the same available energy for mixing. This can be viewed as a competition between grid-scale motion and sub-grid parameterisation. For example, the more efficient non-local-mixing PBL schemes may stabilise the boundary layer before resolved eddies can form, thus suppressing the resolved eddies. This is not to say that the combined effect of dynamics and parameterisation is correct in the terra incognita grey zone, and research is needed on physics that can work optimally with dynamics at these scales.

A pragmatic approach for the region of grid spacing 100 m < Δx < 300 m would be to still use the Reynolds-averaging approach. Generally, it is recognised that three-dimensional mixing is required (which may mean LES!). Therefore, fully prognostic three-dimensional TKE schemes (with TKE advection) might be an appropriate modelling choice, and this type of PBL parameterisation has already been implemented in some meso-scale/cloud-scale models (WRF, UKMO’s UM, ARPS, see also workshop summary of Hong and Dudhia 2012).

The aspect ratio (ratio of vertical to horizontal grid size) for LES should be close to 1:1 (Lundquist et al. 2010). Often meso-scale model grids will have $\Delta x > \Delta z$ (or even $\Delta x >> z$), at least close to the ground, thus making it questionable whether the concept of TKE without differentiating between the contributions of horizontal and vertical turbulent motion can be used in a three-dimensional turbulence approach. In such cases, at least the mixing length scales should consider different grid sizes in each direction. Anisotropy in length-scales may also arise from stability considerations.

[3] Note that this is not a specific ‚complex terrain’ issue – tests and comparisons could also be made over flat terrain (at least in principle)

Considering the initialisation of turbulence in the atmospheric boundary layer (ABL) is as important under neutral and stable conditions as under convective conditions where inhomogeneities of the surface heat flux are sufficient to start off convection. Compared to flat terrain, in complex terrain resolved turbulent motions may be initiated more easily due to sub-grid terrain-induced eddies. Two approaches for generating turbulence are proposed: recycling (or quasi-periodic conditions) and by using large domains with a long fetch. With the recycling approach, the turbulent fluctuations generated at a certain location (could be the outflow boundary) downstream from the inflow boundary are added at the inflow boundary. This is similar to periodic boundary conditions but with the turbulent fluctuation rescaled at the inflow boundary. In general, turbulent boundary layers develop as the flow passes through the computational domain from the inflow boundary, which means that the boundary layer depth increases as the flow passes through. Therefore, if we introduce turbulent fluctuations developed at the outflow boundary into the inflow boundary based on the ordinary periodic condition, the depth of the turbulent boundary layer continuously increases at the inflow boundary. In order to avoid this unphysical development of the boundary layer, we need to control the boundary-layer depth to be unchanged during the time integration. For this purpose, the turbulent fluctuations at the downstream location should be rescaled to the initial depth of the boundary layer at the inflow boundary. The large domains approach, on the other hand, allows the flow to develop an appropriate turbulence state over a large distance (i.e. long fetch) upwind of the area of interest. For this the streamwise length of the domain to generate turbulence should be 20 times the depth of the boundary layer, or 5 times the depth of the computational domain. Of these two approaches, the former may not always be necessary for flows in complex terrain, because complex terrain will generate a sufficient amount of turbulence. A recycling method may be a choice when one considers quick generation of turbulence to be used for reproducing fully turbulent flows over the area of interest. A number of types of recycling methods have been proposed for meteorological applications (Mayor et al. 2002, Nakayama et al 2012). A large domain approach is used for simulating turbulent flows over roughness obstacles (Nakayama et al. 2011).

The dissipation length scale applied by models within the 'terra incognita' is based on Kolmogorov's law which is, however, valid only in the inertial sub-range. It is unknown whether large eddies created in models with grid spacings of 100-300 m are dissipated appropriately.

4.2.2 Complex terrain effects for surface processes

There are several issues that require further attention regarding the complex terrain effects for surface processes:

Radiation. The solar radiation calculation needs to refer to the direction normal to the sloping surface and consider shading by topography. Some off-line implementations do exist, for example in COSMO (Buzzi 2008, based on Müller and Scherer 2005), which do not require excessive additional runtime. Another aspect is that with high resolution, vertical column radiation models might not be appropriate, because clouds can be of very small scales. The issue is how to treat moving clouds and possibly a stochastic approach may be necessary. This, in turn, might introduce problems with clouds in preferred (e.g. mountain top) locations. Addressing slope effects on radiation is generally required when the grid size is small enough to resolve individual slopes, which may start below some 2 km grid spacing. This effect is easy to add, and it is included in several mesoscale models including WRF, ARPS and MM5, but requires an estimate of the direct versus diffuse part of the solar radiation at the surface. Consideration of topographic shading is only required at even higher resolution, but of course only with steep topography. This can be complicated in parallel computing because it requires the calculation of non-local shadowing effects that at fine resolution may extend over many grid cells. It was also recognised that sub-grid slope effects in coarser grids do not cancel out in general, which is a possible error source for coarse models.

The validity of Monin-Obukhov theory. Empirical similarity relations for the surface layer have most generally been devised based on data from horizontally homogeneous and flat terrain and it is not a priori clear to what extent they apply in complex terrain. There is, however, some evidence (e.g., de Franceschi and Zardi 2003) from quasi-homogenous surfaces in complex terrain that surface-layer relationships may be valid, provided that careful analysis (and possibly slight reformulation) is applied. Two types of problems were discussed: i) the assumption of horizontal homogeneity (which, for very high-resolution modelling may not be the dominant problem); it is part of most similarity relations and thus cannot truly apply in complex terrain; ii) momentum exchange: most models parameterise momentum exchange through shear stress alone. On valley slopes, however, directional stress may be on the same order of magnitude (Rotach et al. 2008). Some implementations (e.g., the COSMO model) have a description of the directional stress, but it still depends on the vertical gradient of longitudinal (not the lateral) component of the flow. Generally, surface-layer model formulations need to take into account the three-dimensionality and spatial heterogeneity of the turbulence in complex terrain.

Gravity wave drag is sometimes also implemented with a directional sub-grid effect (e.g., Kim and Arakawa 1995). This is needed for grid sizes greater than about 10 km over mountainous regions in order to represent an important sub-grid component of the momentum flux that affects the jet stream level.

Albedo, snow cover, soil moisture. These parameters are very important for thermally-induced flows, energy and water budgets, etc. Soil models are mostly vertical and one-dimensional, but in mountainous terrain, some aspects such as run-off (at the surface or within the soil) would need to be two- or three-dimensional. There would be a sink of soil moisture for sloped areas and a source for valley areas affecting soil moisture evolution. Coupling of atmospheric with hydrological and snow models may be necessary for proper simulation of thermally-driven flows, i.e. the proper timing for the onset of the valley wind (e.g., Chow et al 2006, Szintai et al. 2010). This would also have to account for the water table and bedrock depth. The question is to what extent this should be off- or on-line, and to what extent the initial soil fields are consistent with these terrain effects.

Surface wind biases. Models often produce too high wind speeds over flat areas and valleys, because unresolved sub-grid topography causes additional surface stress that is not represented. Several models attempt to compensate for this by either directly adding a stress term, or through an increased roughness length, depending on the sub-grid elevation variance. The former method may be preferred because changing the roughness length has side effects on the heat and moisture fluxes. It was also recognised that modelled wind seems often to have a low bias at hill or mountain tops due to not accounting sufficiently for the exposure to the upstream flow (see Fig.18 and Jimenez and Dudhia 2012).

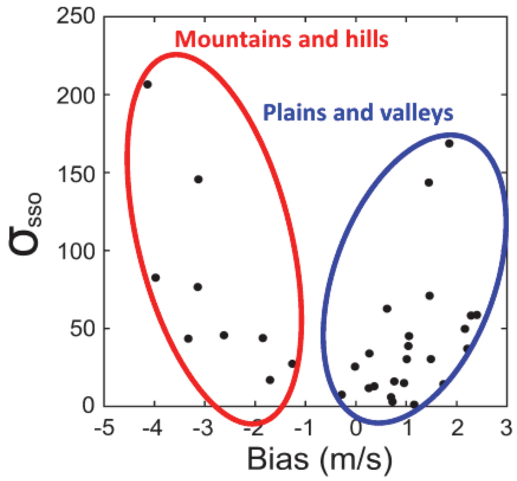

Fig. 16: Standard deviation of sub-grid orography versus wind speed bias for a 2 km northern Spain domain. This shows low bias at mountain peaks and high bias in plains and valleys (Jimenez and Dudhia 2012)

Other issues may include treatment of urban areas, seasonal changes in vegetation. These might be, however, of secondary importance in complex terrain.

4.2.3 Developments in parameterisations

There is a need for observational evidence, intercomparison and validation of parameterisations. Generally, available data stem from field campaigns, and thus are for limited periods of time. Furthermore, as they may have already been used in the development of parameterisations, there is not much opportunity to independently check them. Recent campaigns covering also spatial variability in complex terrain include the MAP Riviera project (Rotach et al. 2004), T-REX (Grubisic et al. 2008) and COPS (Eigenmann et al. 2010). Planned activities include the i-Box (Stiperski et al. 2012) around Innsbruck (Inn Valley, Austria) where long-term detailed turbulence and boundary layer observations are planned, HYMEX (http://www.hymex.org/), and the Materhorn project (Fernando 2012).

A model intercomparison for 'complex terrain' has been performed using idealised topography (Schmidli et al. 2011). Recent examples for comparisons between single models and field campaign data are the comparison of the Riviera data with ARPS (Chow et al. 2006, Weigel et al. 2006) and RAMS (De Wekker et al 2005) simulations. Systematic comparisons between model (MM5) and observations are also available for VTMX sites (Lee et al 2006)[4].

A model intercomparison study in real complex terrain seems to be missing. Such a model intercomparison should consider the following questions:

– Which observational data are needed? For example, one may wish to ask for turbulence observations at several, maybe many, sites, vertical profiles throughout the boundary layer, remote sensing, mean meteorological data. In principle, knowledge of the full three-dimensional flow and turbulence structure in a certain area would be desirable. Most crucial, but difficult to obtain would be three-dimensional turbulence information including profiles which can be determined from airborne platforms (small research aircraft or unmanned aircraft) or a possibly scanning Doppler lidar. Efforts are underway to develop tethered balloons systems supporting turbulence probes.

[4] This list is by no means exhaustive – the authors are happy for any further literature suggestions.

- Accurate external data such as high-resolution land-use information with its related surface parameters (including state of vegetation), soil moisture, and snow cover.
- Should one compare a single model with several PBL schemes, or several models with a single PBL scheme (or even a mix thereof)? Both strategies will yield important (but different) information, so that opportunities (project environments, etc.) should be realised as they emerge.
- A test-bed for boundary layer processes in complex terrain should be based on more than just episodic data[5], so that model behaviour can systematically be tested over a range of conditions. A long-term observational program, along with numerical modelling activities, as in preparation in the i-Box (see above, Stiperski et al. 2012), seems to be necessary.

The necessary work on parameterisations can follow different paths:

Modification of existing schemes. For example, adding auto-conversion and vertical velocity for microphysics schemes. Some microphysics schemes will be tested in Hymex (http://www.hymex.org/), where also 'non-conventional measurements' such as aerosols and droplet size distributions will be available. Another example would be to add explicit height dependence to existing schemes (e.g. Mosaic or Ghan approaches to treat sub-grid-scale spatial heterogeneity, SnowPack to model the variability of the snow pack), so as to allow for more appropriate parameter setting in complex terrain. For climate or long-term studies related to water resources, precipitation and snow pack, it is critical to resolve the elevations of the mountains and snow pack sufficiently. Rasmussen et al. (2011) found that grid sizes below about 6 km were required for reasonable snow accumulation in the Colorado Rocky Mountains. For long regional climate runs, this is still computationally prohibitive, so other approaches may be needed. For example, Leung and Ghan (1995) used a mosaic approach with a classification by elevation to capture effects of sub-grid elevation variation within a grid cell when it was poorly resolved by the regional climate model. Precipitation type, vegetation and soil behaviour are treated separately in each elevation class. Similarly, a parameterisation of sub-grid-scale topography and land use is implemented in the regional climate model RegCM3 (Giorgi et al., 2003) which uses a regular, fine-scale surface sub-grid for each coarse model grid cell. Near-ground temperature and water vapour are scaled down from the coarse grid to the fine grid, land surface calculations are then performed separately for each sub-grid cell, and surface fluxes are re-aggregated onto the coarse grid cell and fed back to the atmospheric part of the model. The downscaling is based on the elevation difference between sub-grid and coarse-grid cells and uses a standard vertical temperature gradient (which may be unrealistic for certain conditions). Unfortunately, precipitation cannot be scaled down by such a simple approach although it is affected by sub-grid topography; at least, convective precipitation is randomly assigned to 30% of the sub-grid cells. Despite these limitations, this scheme has shown an improvement of the fine-scale structure and overall simulation of surface air temperature over complex terrain, and a more realistic simulation of snow pack (Dimri, 2009). The improvement in snow pack simulation is especially relevant for hydrological parameters such as the seasonal variation of run-off (Formayer and Nadeem, 2009). In summary, the sub-grid approach can provide an effective tool to bridge the scaling gap between climate models and surface hydrological processes, although further improvements are desirable.

New schemes. Processes that will potentially require new schemes include sub-grid-scale parameterisations for micro-scale effects in local circulations, turbulence and pulsations in rotors and downslope windstorms.

[5] i.e., the "golden day" from one of the field campaigns

Sub-grid scale orography and its effect on the momentum budget. Wind speed biases tend to underestimation over mountain tops and overestimation in valleys (see Fig. 18). Jimenez and Dudhia (2012) showed that for WRF making the surface wind less sensitive to surface roughness at objectively defined mountain-top locations can alleviate the underestimation there. This decoupling also improves the diurnal cycle, which has a midday minimum of the wind at hilltops (contrary to the maximum in plains and valleys) – these locations are more similar to the upwind upper boundary layer. The parameterisation by Jimenez and Dudhia (2012) also considers the sub-grid terrain features for plains and valleys to alleviate the high-wind bias there, and the two changes together enhance the surface-related variability over complex terrain. This is important for wind-energy applications.

Sub-grid parameterisations for coarse-scale models. Several of these were discussed:

– Chao's (2012) parameterisation for ventilation due to unresolved thermally-induced flows helps to reduce positive bias of precipitation over large-scale mountains;

– Gravity-wave drag parameterisation for upper winds (e.g., Lindzen 1981; Palmer et al. 1986);

– Blocking parameterisation for boundary-layer winds, e.g. Zadra et al. (2003).

5 Thematic area 4: Initialisation and input data

5.1 Background

All models at very high resolution, whether used in forecasting, for climate simulations or for episodic studies need atmospheric and surface initialisation and lateral boundary data, and static input data for the simulation domain. Initial and boundary values are usually provided by global models (sometimes also operational limited-area models) via coupling data prepared for the nesting domain on the one hand and via measurements on the other hand. The static input data characterise the properties and state of the surface, such as topography, soil texture, albedo, LAI, vegetation fraction, and land cover. The data which come along with standard models such as WRF usually have a resolution of at most 1 km, while coupling data and measurements are provided at even lower resolution. So, atmospheric and surface initialisation is mostly done using data of much coarser resolution than the resolution of the high-resolution model.

For the regional and local-scale simulations in mountainous and hilly areas, the correct representation of the topography and surface properties is a key factor. In order to build the information on a 1 km computational grid, that will in general not coincide with the grid of the supplied data, these data should have a higher resolution.

5.2 Land surface datasets

The correct representation of the land surface has been recognised as an important issue in general (Koster et al., 2004, 2009, 2010, Chow et al. 2006, Weigel et al., 2006, 2007, Maxwell et al., 2007, Mahanama et al., 2008). Land surface characteristics include topography, water bodies, soil characteristics, land cover and vegetation characteristics, urbanised locations, albedo and emissivity properties. While some characteristics can be considered static (e.g. topography) others change with time and may be influenced by the state of the land surface (e.g. albedo). Unfortunately, surface data, such as land cover information, often date back to the mid-1980ies or early 1990ies (Pineda at al. 2004). Meanwhile, conditions may have changed due to de- or afforestation, growth of urban and sub-urban areas, changes in agricultural use, and many more. Thus, to adequately simulate local meteorological processes highly resolved and up-to-date surface data are desirable.

A particularly important factor in meteorological modelling is the initialisation of soil variables. Slowly changing variables, such as soil moisture and temperature, have a strong influence on the surface fluxes and thus on the local dynamics. Data used for standard initialisation are typically at coarse resolution and thus neither represent the effects of the real land-use, nor, even more importantly, features associated with topography such as cold air pools in valleys and basins during the cold season. The soil has a long memory and thus a certain amount of spin-up time needs to be taken into account, the more the initial conditions deviate from reality. Episodic simulations cannot afford month-long spin-up and need a different kind of treatment, for instance, by running off-line land surface models.

The mapping of the land surface characteristics to the surface parameters required by the land surface model (LSM) is a complex undertaking and also partially LSM specific, as different LSMs may need different surface parameters. As an example, Figure 19 illustrates how land surface characteristics from different data sources are combined to create the ECOCLIMAP-2 database (Faroux et al., 2009, Tchuente et al. 2011), containing the surface parameters required by the ISBA LSM (Noilhan and Planton, 1989, Noilhan and Mahfouf, 1996).

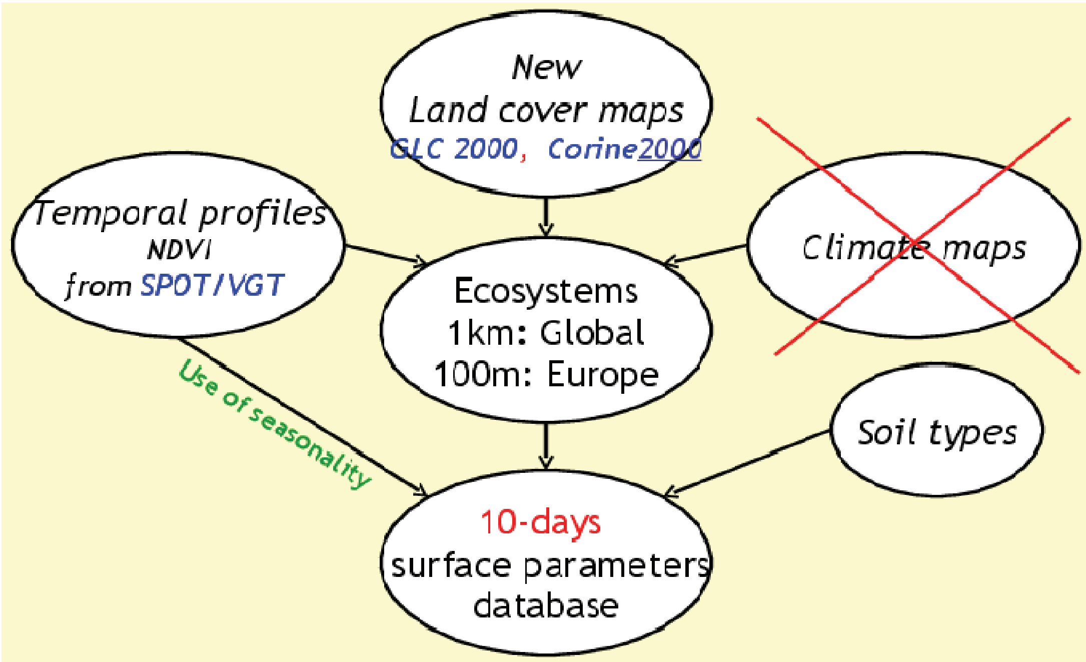

Fig. 17: Mapping of land surface characteristics to surface parameters as exemplified for the ECO-CLIMAP-2 database (Figure from Faroux et al. 2007). Climate maps are not anymore required as input data, in contrast to ECOCLIMAP-1.

To be able to improve the representation of the land surface over complex terrain, one needs to work on each single surface characteristic.

5.2.1 Elevation

High-resolution simulations of 1 km or finer grid size in complex topography require accurate digital elevation model (DEM) data with a grid cell size of about 100 m or even better. Such high-resolution data sets are usually not implemented in the default model versions. High-resolution elevation data in most models is limited to 1 km data sets, the majority of models using the GTOPO30 (30”) USGS product. When performing simulations with resolutions close to 1 km this implies that smoothing of high-resolution topographic features occurs, with lower mountain peaks and elevated valley floors. It would be desirable to have input DEM data with a resolution exceeding the model resolution by at least a factor of 2 to 3.. Topographical data sets with 3” (about 100 m) or even 1” (roughly 30 meters) resolution are available for many areas of the world. However, their ingestion is not straightforward and some issues regarding mislocation of the topographical features may appear.

Topographical data are available in 3’’ resolution nearly worldwide from the Shuttle Radar Topography Mission (SRTM). ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data come with 1’’ resolution. A problem for both is the steep terrain where errors can be present (shadowing, calculation of topography). Sometimes also national laser scanning data exist, but usually they are not freely available.

5.2.2 Land cover and soil texture datasets

Default land cover data in the models are usually from the early 1990ies and include a rather small number of different land cover classes, not representing, for example, different kinds of urban structure. Their resolution of 1 km is often too low for high-resolution simulations. Furthermore, the quality of the classification is not always satisfactory. Therefore, it is desirable to implement modern land cover datasets such as the European CORINE data (100 m resolution, 44 categories). Alternatively, ECOCLIMAP-2 (Tchuente et al., 2010) with 1 km resolution can be used. MODIS data with 20 different classes are already built into many models, having the advantage of being globally available. On the other hand, 20 classes are the lower limit for the number of land-use classes. The USGS data, still widely used, are outdated and too coarse for sub-km resolutions. Also, in some regions the accuracy of classification is not good. Still, for some regions it can be the best one can get.

Implementing high-resolution land cover datasets requires further information as the land cover data are only a means for assigning values to parameters such as roughness length, albedo, LAI, and vegetation fraction to each grid cell. These parameters can be taken from published literature, or derived using remote sensing data or agro-meteorological models (as in ECOCLIMAP-2).

Soil texture used in the models is typically based on the FAO soil type classification (FAO Digital Soil Map of the World, FAO/IIASA/ISRIC/ISSCAS/JRC, 2009). Obtaining data with higher resolution based on this classification is not easy. Soil texture is an important parameter as it determines the thermal and hydrological properties of the soil. It has a large influence on the runoff and it also defines the soil and root depth. Where data is lacking, this is still an important topic, which should be worked on in the future.

5.2.3 Time-dependant surface datasets

Nowadays, satellite-based data are available for many of the required surface parameters, such as LAI, vegetation fraction, albedo, snow cover and superficial soil moisture. To be able to substitute the standard data built into the model, one needs to derive climatological values. Although most of these satellite datasets come with resolutions of only 500 m – 1000 m, a bit too coarse for simulations with grid cell sizes of 1 km and below, this is still better than using the outdated surface parameters included in the default datasets.

Vegetation coverage, snow cover, albedo and soil moisture may vary in time, as a function of the seasons, but also in response to weather and biospheric changes during a specific period of time. For accurate simulations at a scale where the lower boundary condition exerts a decisive influence on the atmosphere, it is desirable to have as much and as accurate pertinent information as possible, and certainly more than the standard information provided with the models. Thus it could be valuable to make use of the time-dependent information provided by the satellite platforms.

Albedo is one of the key parameters and it may have pronounced temporal changes. The albedo values used in models usually are based on climatological mean values per month and with rather coarse resolution. One way of improving this would be to use the actual albedo for the period of interest as derived from satellite data. In cases where this is not possible, such as for climate change simulations, one tie the albedo values to the land cover and vegetation state (seasonal cycle) of the corresponding grid cell.

Other gridded data sources (e.g. data provided by the FAO) and tools such as the Land Information System (LIS, Kumar et al., 2006), a high performance land surface modelling and data assimilation system, the NASA SPoRT project (http://weather.msfc.nasa.gov/sport/), and the Austrian LISA (http://www.landinformationsystem.at/) could also be useful. While the NASA SPoRT project is devoted to improve regional-scale forecasts by transitioning observations and research capabilities to the operational weather community, short-term and long-term simulation efforts could also benefit.

Soil moisture distribution often proves important, e.g. for the development and timing of thermally driven flows (e.g., Chow et al. 2006, Szintai et al. 2010). Data from large-scale models are, however, usually not of sufficient quality. As a possible way out, Chow et al.

(2006) have used an off-line hydrological (run-off) model in conjunction with available soil moisture measurements in order to produce high-resolution soil moisture fields for their domain. Depending on the focus of interest, rather crude corrections of the surface conditions such as soil moisture and snow cover can sometimes be sufficient (Schmidli et al. 2009). Satellite-based remote sensing products (e.g. downscaled ASCAT superficial soil moisture; Wagner et al., 2012) do not seem to be sufficiently mature in their ability to yield sufficient accuracy and resolution, especially to account for the variability in complex terrain.

5.3 Land surface initialisation and assimilation

Soil moisture is an important parameter especially in climate modelling and complex terrain. To correctly represent the soil-atmosphere interaction, the soil parameters need to be initialised correctly. Data from forecast or global / regional climate models are often the best one can get for some regions. Studies (Dharssi et al., 2010, 2011, Han et al., 2012, Draper et al., 2011) showed that assimilation of soil moisture (satellite data, station data) including the lower surface observations (2 m temperature, humidity and wind) can improve simulation results. Unfortunately, a high station density is needed for proper high-resolution assimilation. This is a problem in complex terrain – even if the density of stations is good, they will probably not be representative for the different kinds of terrain. Data assimilation is useful for episodic case studies, but climate studies need a different way of dealing with the land surface.

One way of initialising climate simulations is to use a long period of spin-up, thus giving the soil and land surface enough time to "forget" the initial conditions, hopefully approaching and not drifting away from the real state of the system. Another possibility is the use of off-line soil models to generate the soil input data for the meteorological model. The drawback of off-line models is that they require gridded input data to be generated from observations. Like in the case of data assimilation, this requirement is not easily fulfilled in complex terrain, because station data density is usually inadequate relative to the variability caused by terrain and surface properties.

In-line use of soil models during the forecast run for appropriate soil conditions is standard nowadays for NWP models on global and regional scale. Nevertheless, these models, like SURFEX (Surface Externalised; LeMoigne, 2009), H-TESSEL (*H*ydrology-*T*iled *E*CMWF *S*cheme for *S*urface *E*xchange over *L*and; Balsamo et al., 2009) or JULES (Joint UK Land Environment System; Blyth et al. 2006) are suffering from the lack of high-resolution data (both in–situ and from satellite) in complex terrain and inadequate formulation of equations for the kilometre-scale so far.

Information on snow and albedo can be retrieved from satellite data, even at relatively high spatial resolution. In some regions cloud cover could be persistent, temporal resolution may be an issue and thus spin-up (or in the case of operational forecasts, re-using output from the previous run) may be the more realistic approach. Satellite-derived snow cover products can be used for initialising the snow pack in the model, e.g. by initialising a low water equivalent snow pack. Water bodies and their initialisation is another relevant issue. A standard approach is to assign the SST from the nearest sea grid point to any lake grid point. Obviously, this can result in highly unrealistic temperatures. Therefore, skin temperature is often used instead of SST. Another approach would be using the satellite data or in-situ measurements. For NWP or case studies this would be appropriate, for climate simulations either skin temperature or maybe climatological values derived from satellite data could be used. Especially in (regional) climate studies the initialisation of the oceans and lakes included in the modelling domain can be crucial (Konovodov, 1972, Rockel, 2010). Thus, for climate simulations a one-year spin-up time should be used.

5.3.1 Off-line land surface models

One way of deriving proper land surface information is to use off-line land surface models which generate initial conditions for the mesoscale and climate models. One of them is the High Resolution Land Data Assimilation System (HRLDAS) tool, which was developed for the purpose of driving a land-surface model as the Noah land surface model off-line, from observed data, during a spin-up period with subsequent use of the results as initial conditions for WRF runs. Gridded fields (observations, satellite, reanalysis fields) and observation (point) data are used as input to the off-line land surface model(s) and moisture and other surface fields as initial condition are provided for the WRF or other mesoscale models using a similar system.

5.4 Atmospheric initialisation and assimilation

Proper lateral boundary conditions are a precondition for high quality mesoscale simulations. Usually, a global (synoptic-scale) operational model which has, by definition, no lateral boundary problems provides both the initial and boundary conditions. The data from such a model have to be scaled down to the grid of the mesoscale model. Also, during the simulation, the fields from the outer nests have to be scaled down to inner nests in a transition zone when using a nested set-up. Downscaling (interpolation) is needed both spatially and temporally. Global models run with time steps of typically ~15 min, but their output is available at intervals of hours, e.g. 3 h. Mesoscale LAMs often run with time steps closer to about 5 min and significantly less for very high resolution. The actual lateral boundary data are created by interpolating these, e.g., 3-hourly global-model data to create a time series with, e.g., 5-min resolution. In spite of nominal high temporal resolution, the lateral boundary condition used will not contain physically meaningful information on time scales smaller than 3 h (Termonia et al., 2009). For small-scale features or fast moving systems, it is necessary to decrease this coupling time interval. Concerning the spatial resolution, there are two guidelines. The first one is to utilise a lateral-boundary buffer zone so the lateral boundaries are sufficiently far away from the area of meteorological interest within the domain. As thermally-driven flows react to conditions in a whole valley system, this area of interest may be quite large, depending on the topographic features and meteorological conditions. The second guideline is to avoid strong forcing at the lateral boundaries. This guideline pertains specifically to strong orographic forcing. So, it is recommended to set the domain boundaries in a way that they do not intersect steep orography (Termonia et al., 2009). As the topography will be better resolved in the inner nest, with deeper valleys and higher ridges, vertical extra- and interpolation is done. Usually, this is done with climatological temperature gradients for temperature. Temperature may then feed back on other quantities such as absolute moisture and pressure, and may influence also the soil parameters. However, climatological temperature gradients can be far from reality, especially if the valleys are filled with cold air pools. Obviously, there is a potential for model improvement.

Spin-up times for case studies are case dependent and will obviously need to consider also the length of the simulation and the available computational resources, but as a rule of thumb one could specify at least 12 hours of spin-up (atmospheric spin-up only!). For climate simulations, it is necessary to give the soil at least one year of spin-up, as soil has a longer memory, and initial conditions could be relatively far from reality. Note that there is no guarantee for the spin-up to develop properly if there are feedbacks and tipping points in the system, e.g. related to snow cover.

Data assimilation at the convective scale poses numerous challenges (Caya et al., 2005). While for global models data density, especially due to the extensive use of satellite measurements, is reasonable, this is not the case for very high-resolution modelling. Neither atmospheric satellite nor screen-level measurements (mainly from ground station networks) are available in the required resolution and density, apart from special research networks like the “WegenerNet” with one station per 2 km^2 (Kirchengast et al., 2008) or the temporary COPS network of the University of Vienna with one station per 1 km^2 (Stuhl, 2008). Thus, the use of all available data sources including radar (with a typical grid size of 1 km) and vertical GPS water vapour monitoring (e.g. Gendt at al., 2004) as supporting source for radio soundings is of interest for high-resolution modelling. However, it should be noted that water vapour monitoring has a coarse horizontal resolution (40 km for the case of Austria) and its applicabitlity to places with complex topography might be not easy to address.

Due to increasing computer power, 3D-FGAT (3D-Var with First Guess at Appropriate Time; Massart et al., 2010), 4DVAR (e.g., Huang et al., 2009, for WRF) and ensemble Kalman filtering (e.g., Caya et.al, 2005) are state-of-the-art for numerical models nowadays for making use of the temporal evolution of observed meteorological parameters.

Not all data sources are equally important for the forecast quality. Tests with AROME showed that surface observations, aircraft and radar data have the largest positive impact (Brousseau et al., 2012), while satellite data are adding just small improvements to the forecast quality, as the information they are providing is already assimilated in the global model to which AROME is coupled. Radar is supposed to be a very important data source due to its high spatial and temporal resolution, even though it provides data mainly for areas with precipitation. For example, the operational assimilation of radial velocities from Doppler weather radar at Météo France resulted in an improvement of the spatial structure and the quantitative performance of precipitation forecasts because of better analyses of low-level convergence (Seity et al., 2011). The assimilation of radar reflectivity is still under development as it is not that straightforward. One promising approach is described in Caumont et al. (2010), using a combination of 1D+3DVAR.

5.5 Data sources

- ASTER GDEM http://www.ersdac.or.jp/GDEM/E/index.html
- SRTM data http://www2.jpl.nasa.gov/srtm/
- CORINE CLC 2006 http://sia.eionet.europa.eu/CLC2006/
- GlobCover 2009 (300 m; http://ionia1.esrin.esa.int/)
- GlobCarbon 2007 (LAI and fPAR at 1 km; http://dup.esrin.esa.it/prjs/prjs43.php)
- MODIS products http://modis.gsfc.nasa.gov/data/dataprod/
- FAO soil information http://www.fao.org/nr/land/soils/en/
- HWSD (JRC) 2009 (1 km; http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/)
- European Soil Data Base (ESDB), http://eusoils.jrc.ec.europa.eu/esdb_archive/ESDB/SOTER, http://eusoils.jrc.ec.europa.eu/projects/soter/
- ECOCLIMAP-2 (http://www.cnrm-game.fr/spip.php?rubrique87&lang=en)
- LSA SAF, http://landsaf.meteo.pt/

6 Conclusions and outlook

6.1 Conclusions

Four thematic areas have been identified and discussed which are relevant for atmospheric modelling in complex terrain, especially high mountains, at grid spacing on the order of 1 km or less.

With respect to computational issues, it was noted that practical problems are large, in the sense of domains having a high number of grid points. Standard computational benchmarks do not consider this. More realistic benchmarks have been developed. The most relevant bottleneck at the moment is the amount of output that is produced for such large problems. Solutions can be based on different I/O techniques not relying on a single node (more parallel), and on a reduction of the amount of output, e.g. by finer granularity of output options.

In terms of numerical schemes, there are issues which may be considered solved, and others that need development. Implicit numerical diffusion should be minimised through the selection of appropriate numerical schemes. Explicit horizontal diffusion should be implemented to be truly horizontal, and not use higher than 2nd order derivatives to avoid coordinate slope effects. High resolution requires very short time steps, especially in the vertical. Schemes that apply the shorter time steps only when and where needed can help. Fully or partially implicit time discretisation would also be useful but requires work for efficient parallelisation. In terrain steeper than about 40 to 45° current levels of discretisation reach their limit. The limit can be extended by a more refined implementation of the pressure gradient term. Further extension towards steeper topography will require other, e.g. Cartesian, coordinate systems, even though they entail disadvantages. Until substantial progress is realised, appropriate smoothing of the terrain needs to be performed.

The parameterisation of turbulence in the atmospheric boundary layer will need more attention, as three-dimensionality of turbulent processes become relevant at larger spatial scales over complex than over flat terrain. Recommended parameterisation schemes should be based on a budget equation for the turbulent kinetic energy, including advection, and possibly also differentiating horizontal and vertical contributions. Contributions from horizontal shear can also be relevant. Nested simulations with a LES domain as the innermost nest may be targeted for research purposes, but proper nesting methods need to be developed. Radiation needs to consider shading by topography and should consider the three-dimensional nature of the shading by clouds, although this is also a challenge in the numerical implementation. There is evidence that sub-grid terrain roughness effects on the momentum budget should be parameterised to obtain less biased wind speed distribution. Finally, realistic benchmark cases, including suitable observational data sets to test, intercompare and validate both new and existing models with respect to their ability to properly represent basic properties of flows in mountainous terrain, should be prepared.

The relevance of the (partially) static model input data of surface properties grows with higher resolution and, due to the strong horizontal variability caused by elevation differences, is of special importance in complex terrain. Standard data sets supplied with models such as WRF are not sufficient, neither with respect to spatial resolution nor with respect to accuracy and degree of detail. SRTM 3" digital elevation data should become a directly implemented alternative to USGS 30" data. In Europe, the CORINE land-use data should replace the standard global data sets. However, more work is needed to assign appropriate values for albedo and soil parameters in each of its land-use classes. Proper initialisation of model runs is still not a solved issue. For the state of the surface and soil, use of satellite data (for example for snow cover or state of vegetation) and of off-line land models and/or hydrological models should be explored and developed further. Atmospheric initialisation as well as interpolation of lateral boundary conditions at domain boundaries intersecting topography is also a problem; climatological vertical gradients should be replaced by more realistic approaches. These problems are worse for episodic simulations, whereas climate simulations may alleviate them through spin-up, and operational forecasts by recycling of forecasts as initial conditions, and/or ensemble techniques.

A number of issues that came out of this workshop and its conclusions are left open at this point and will have to be answered and addressed by future research activities:

- How far can terrain-following finite difference methods go and what is the potential of computational fluid dynamics (CFD) approaches?
- How to set up LES simulations for realistic complex terrain?
- What are the best and most feasible options to carry out and post-process large simulations in supercomputing facilities?

A test bed for complex terrain simulations is needed with high resolution observational data to allow model intercomparison based on real data.

6.2 Detailed recommendations

It was considered desirable to prepare a more detailed document of issues in high-resolution modelling of the atmosphere in complex terrain, directed primarily at model users, but also as a reference for those who are interested in contributing to model development, including development of model input data. For all the thematic areas, this should contain

- list of challenges,
- existing solutions,
- work to be done.

This is not a small task and there was agreement that it would not be a direct outcome of the workshop. Probably, it would be most useful and feasible to do this just for the WRF model, since it is so widely used.

6.3 Follow-up workshop

Participants agreed that it would be desirable to have a follow-up workshop with a similar format within a time horizon of two to three years (i.e., 2014 or 2015). More room should be given to presentations of new developments and solutions, but still leave enough time for a broad discussion. In addition to overviews by "designated participants," a few 10-20 min presentations selected or invited by the "designated participants" and/or the organisation committee were considered useful, but the general structure should remain flexible and allow interaction. For the presentation of results, posters were considered useful. Possible locations for such a workshop were left open.

6.4 Other follow-up activities

It was discussed whether a WMO forecast & demonstration project would be desirable. This would be related to an operational context, e.g. the Sotschi Olympic Games where several national meteorological services will provide forecasting services, for example Canada and Japan.

Another option for more formalised cooperation would be a European COST Action. There is no aim for this at the moment, but in principle that might be attractive as a future option.

The HiRCoT wiki (http://met.boku.ac.at/hircotwiki) should be kept as a basis for collaboration and collection of literature, links, etc. It shall be made readable for the public, and new contributors will be welcome.

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