PUBLIZIERBARER Endbericht Studien

(gilt nicht für andere Projekttypen)

A) Projektdaten

Titel:	High-resolution atmospheric modelling in complex terrain for future climate simulations
Programm:	ACRP 1st Call for Proposals
Koordinator/ Projekteinreicher:	Univ.-Doz. Dr. Petra Seibert
Kontaktperson - Name:	Univ.-Doz. Dr. Petra Seibert
Kontaktperson – Adresse:	Institut für Meteorologie, Peter-Jordan-Strasse 82, A-1190 Wien
Kontaktperson – Telefon:	01 / 47654 5613
Kontaktperson E-Mail:	petra.seibert/at\boku.ac.at
Projekt- und Kooperationspartner (inkl. Bundesland):	
Projektwebsite:	http://www.boku.ac.at/met/envmet/hirmod.html
Schlagwörter:	
Projektgesamtkosten:	153.458
Fördersumme:	152.688
Klimafonds-Nr:	A963694 / AC0K00023
Projektstart & Ende	15.10.2009 - 31.01.2012

B) Projektübersicht

1 Executive Summary

The creation of climate-change scenarios at km-resolution in mountainous terrain is an unsolved problem although climate-change impact studies urgently need this. HiRmod prepares for the time in the near future when computers will be powerful enough to accomplish this aim by dynamical downscaling with nonhydrostatic models. Two such models, MM5 and its successor WRF, have been implemented at the Vienna Scientific Cluster (VSC). Detailed performance tests with WRF have identified I/O as a critical bottleneck. To get near the desired capability, the amount of output needs to be reduced, probably the "quilting" method should be implemented, with the aim of using ~5000 cores (ca. factor of 10), and an improvement of single-core performance by another factor of 5-10 (e.g. with Power7 architecture) is required. To adapt static input data to the desired resolution range, standard USGS data were replaced by remapped CORINE land-used data and SRTM digital elevation data. Episodic test runs were performed for regions of interest centred on the southern Black Forest, the Tyrolean Inn Valley, and the Vienna basin, showing positive impact of the new static fields. Further improvements for using the full information in the CORNE data as well as data for soil parameters are desirable. Issues related to initial and boundary conditions were investigated but no solution ready to be realised with this project was identified. Finally, international co-operations have been established, foremost with the Alaska Supercomputing Center / University of Alaska Fairbanks, but also with through an international workshop on high-resolution modelling in complex terrain held just after the end of HiRmod with 32 participants from 13 countries.

2 Motivation and Aims

2.1 Motivation

Future local and regional climate change is a major issue, especially in mountainous regions as in Austria. HIRMOD aims at improving regional climate modelling in the Alps or other mountain regions with steep slopes and narrow valleys. Currently, regional climate simulations are carried out with horizontal resolution on the order of 10 km. This is by far insufficient to properly represent the Alpine topography and their meteorological phenomena. Statistical downscaling does not consider the non-linearities and memory effects which are important in mountain areas. Therefore, dynamical downscaling with nonhydrostatic meteorological models at a higher resolution than 10 km has to be considered as a future approach. Previous studies (e.g. Schicker and Seibert, 2009) showed that the necessary grid distance for resolving the meteorological conditions in larger valleys is on the order of 1 km. In the past years, numerical meteorological models, notably MM5 and its successor WRF, have been improved to be able to work in Alpine terrain at such resolutions and to produce highly realistic results. Still, running these models for climate time scales is out of reach due to their computational costs. We should thus start now to be prepared for the time when this is possible.

2.2 Aims

The main aim of HIRMOD is to prepare for near-future very high resolution climate simulations using non-hydrostatic mesoscale meteorological models such as MM5 and WRF. This includes work on computational aspects, physical parameterisations, static data, and evaluation of very high resolution climate simulation results needs to be done. It is not expected that a project of the scale of HiRmod is able to solve all pending problems, however, substantial contributions towards the aims of the project shall be made and the necessary expertise for such work developed in Austria, also as foundation for further work.

2.3 Structure and Methodology

The structure and methodology of the project is reflected in the work packages:

- **Work package 1** focuses on implementing the two non-hydrostatic models on different platforms and evaluation of the computational costs.
- **Work package 2** deals with the input and observational data needed for the simulation episodes and evaluation of the model results.
- **Work package 3** introduces improvements in the model, performs simulations with the improvements and presents the results.
- **Work package 4** concentrates on the assessment of the results from the afore mentioned tasks.
- **Work package 5** deals with the application of the simulations to dispersion modelling.
- **Work package 6** is the project management including interaction with a group of external expert

3 Content and results

3.1 Motivation for the project

Local and regional climates are strongly influenced by the topography and land-use features on the respective scales. Although the resolution of global climate models (GCMs) has improved, even time-slice simulations currently are done with resolutions of about 100 km which are unable to resolve these local influences. To overcome this limitation, two different downscaling approaches have been established: statistical and dynamical downscaling.

Statistical downscaling identifies analytical relationships between observed meteorological variables at the local scale and the large scale, usually for monthly means. Diurnal values are more difficult to scale down in this way. These relationships are then applied to GCM output assuming that they will be valid in the respective scenario. This approach is computationally cheap. However, it implies that the statistical relationships remain the same in the future, which may not be true, and it is strongly affected by model biases and homogeneity and length of the observational databases. However, for complex terrain like in the Alps, the main problem of statistical downscaling is the fact that real-world relationships between large and small scale are very complicated, involving non-linearities and memory effects, making it very difficult to properly reproduce them with this relatively simple methodology. In spite of the long time for which such approaches have been in use, they are not able, for example, to reliably derive the stability (temperature profiles) inside valleys.

Dynamical downscaling is done by running limited-area regional climate models (RCM) with boundary conditions from a GCM. These models have a proper representation of the physical processes making them in principle capable of reproducing complex relationships. However, this comes at the expense of much higher computational costs, and requires proper behaviour of the model in long-term climate simulations in order not to introduce new errors. Many initiatives have concentrated on developing and improving mesoscale meteorological models to be used as RCMs. State-of–the-art RCMs have been developed either based on existing weather forecasting models, such as the Cosmo-CLM (CCLM) and the REMO model, or from GCMs, e.g., the Canadian Regional Climate Model (CRCM) (Caya and Laprise, 1999). In addition, research-oriented mesoscale meteorological models such as MM5, WRF or RAMS can and are used also for climate simulations (Fernández et al., 2007, Loibl et al., 2007).

At present, the typical grid distance at which RCMs are usually run is 10 km. This may be sufficient when the topography of the simulation area is smooth and land-use is relatively homogeneous. However, for typical mountain topography as found in the Alps, the Black Forest, Pyrenees, etc., 10 km is by far insufficient to produce results that can be compared to station observations or applied to impact studies, since valleys and ridges are only marginally resolved. Simulations with non-hydrostatic models at grid distances on the km-scale have been published in the past years showing promising results (e. g., Zängl, 2002, 2003, 2004, 2007; Schmidli et al., 2009). It is clear that a sufficient number of grid points must be within the valley cross-section to reproduce the atmospheric behaviour inside the valley. Our own work (Schicker and Seibert, 2009) showed that in the middle Inn Valley, 2.4 km grid distance was insufficient while at 0.8 km important features became realistic. This means that the state-of-the-art RCMs should be substituted by nonhydrostatic models to work with resolutions close to 1 km to enable realistic simulations of the climate in mountainous areas.

The more realistic terrain representation is the most important factor for such high-resolution modelling. According to Steinacker (1984), only with a correct representation of the area-height distribution in a catchment area, a proper simulation of thermally driven circulations can be expected. Land-use also needs to be supplied with a sufficient resolution, and all surface parameters need to be available at the necessary horizontal and temporal resolution. This concerns in the first place albedo, soil temperatures and soil moisture, and where appropriate, snow-cover water equivalent. These values are needed for the initialisation (especially relevant as we have to start with episodic simulations) and also for verification.

Computational demands do not increase linearly with horizontal resolution, but at least quadratic or (depending on the implications for vertical resolution and time-step criteria) even with higher powers, and also with respect to RAM and mass storage needs. Although computer power has increased significantly, this is still an important limitation and at the moment, long-term simulations at km-resolution are out of reach. However, we expect that they will become feasible in some years, and thus we should be prepared to use the computer power as soon as it becomes available.

The HiRmod project focuses on implementing and evaluating improvements for currently available nonhydrostatic models to be able to reproduce well the meteorological elements in regions like the Vienna basin, the Inn Valley, and the Black Forest on a scale of 1 km.

Accurate description of the state of the atmosphere in complex terrain is not only important for better understanding of climate change and its impacts, it is also needed to properly use monitoring stations and their observations of greenhouse gases to constrain the fluxes of those gases on a regional scale. Furthermore, meteorological model data is often used as input in chemistry or hydrological models. High-resolution meteorological modelling should help (Seibert and Skomorowski, 2008; Stohl et al., 2009) to make better use of this resource, and guide relocation and/or setting up of new monitoring sites.

3.2 Objectives of the project

Objectives of the project were:

- Prepare for future, very high resolution (~ 1 km) climate simulations in complex terrain when computational resources are available.
- Evaluate and improve – if possible – computational performance of the models used.
- Improve model built-in data as land-use, digital elevation model, etc. to be able to represent the special features of mountainous terrain in the meteorological model.
- Improve / work on the initialisation of the meteorological model in complex terrain.
- Improve the international contacts and communication in the field of high resolution meteorological modelling in complex terrain.

3.3 Activities performed within the framework of the project. Methods employed

Activities and methods are included in the following Section 3.4 on a WP basis.

3.4 Description of results, difficulties and highlights on a work package basis

3.4.1 WP 1: Computational aspects

3.4.1.1 Results

This WP became one of the key aspects of the project, not only because it proved to be of vital importance for the scientific community but also because of the challenges it involved.

Two models are used in HiRmod, the *PSU/NCAR mesoscale model*, *MM5* V3.7 (Grell at al., 1994, `http://www.mmm.ucar.edu/mm5/`), and the *Weather Research & Forecasting Model WRF* (`http://www.mmm.ucar.edu/wrf/`) ARW V3.2.1 (Skamarock, 2008). In order to achieve useful throughput times with demanding set-ups as used in HiRmod, meteorological models need to be run in a parallel mode on computers with many processor cores. Such machines can be shared-memory (SM) machines, where the RAM (random-access memory) can be accessed directly by all the processor cores, or distributed-memory (DM) machines (clusters). The size of DM machines is limited and most high-performance computing facilities including the Vienna Scientific Cluster (VSC)[1] rely on the cluster architecture. The two types of machines require different software support. Usually, it is also possible to use a SM machine with software for DM systems. The performance of most models is not linearly increasing with the number of processors used. Communication overheads will offset a part of the computing power gained with more processors until a maximum is reached.

MM5 was successfully implemented in SM mode in the VSC using the Intel Fortran compiler (ifort) and the GNU Fortran compiler (gfortran). The Portland Group Compiler (pgf) could not be used because the flags defined for previous pgf compilations did not work, and tests for finding a working set of flags did not succeed.

The CPU time requirements and speeds obtained were compared with similar installations at smaller machines available at BOKU, using a benchmark case. The benchmark consisted of a 2-day simulation for the Inn Valley region of interest (ROI) with a model configuration chosen to be close to the simulations to be performed in the project. It included six nested domains, centred around the Inn Valley, with two-way nesting interaction, and with grid distances from 64.8 km, in the outermost domain, decreasing by a factor of three for each nest level until 0.27 km in the innermost domain (202x130 grid cells). All the domains had 39 vertical model layers, with the model top at 50 hPa. To prevent numerical stability problems, a relatively short time step was needed. Results (Table 8.2.1.2 and Arnold et al. 2010a,b) show that even for single nodes and per core, the VSC hardware/software combination is faster than other options available to the project team. It is also remarkable that the model runs approximately twice as fast with the commercial Intel compiler than with the free GNU compiler.

MM5 was successfully implemented in the VSC in a DM mode. However, several problems were encountered while testing compilers, compiler versions and MPI libraries, consuming a substantial amount of time. As official support for the MM5 model has been terminated in favour of the successor model WRF, not all the problems could be investigated. Finally, most of the effort was invested in two combinations, 1) Portland Group version 9.0 Compiler (PGI hereafter) + Qlogic_mpi_pgi-0.1.0 and 2) Intel Fortran Compiler 11.1 (ifort hereafter) + Qlogic_impi_intel-0.1.0. Using PGI, a working solution was not found, whereas with ifort, finally a way was found to obtain a working code. Subroutines written in C (model is written mainly in Fortran) had to be compiled with gcc instead of Intel's icc.

To study the effect of the number of processors on the parallel execution time, the benchmark simulation was done with increasing number of cores, in multiples of 8 to use complete nodes. The execution time decreases until a minimum at 384 cores, where a plateau is reached (Figure 8.2.1.1). The slight increase in CPU time beyond this number could be due to the message-passing communication calls. For production runs, 256 cores would be recommended in terms of an efficient use of VSC resources.

Like MM5, the WRF model had to be implemented in the VSC and tested with different compilers; in addition, it was compared with the predecessor MM5 model. Thus, the same two combinations as for MM5 were used. Opposite to MM5, a working implantation with ifort was not achieved while it was possible with the PGI compiler after some adaptations of the makefiles. According to experiences of

[1] In this report, VSC always refers to the VSC-1 machine. VSC-2, the next VSC machine, only became available for users towards the end of the project and was not used.

other WRF users, small problems may work well with Intel but for large problems, Intel compiler seems to have serious problems. However, since the runs envisaged by HiRmod need large domains and several nest levels, the PGI compiler had to be used, even though one might expect the Intel compiler to perform better on the Intel hardware of the VSC. These experiences highlight that models like WRF are not so easy to use and in the constantly changing hard- and software environments not so little effort is needed to find and maintain a working setup.

In order to investigate the scalability of WRF, a benchmark similar to the MM5 benchmark was used. Apart from the different compilers used, the main differences were that for the WRF benchmark five instead of six nest levels were used, and that the centre of the coarser domain was slightly different. While other users had obtained excellent scalability, our results (Figure 8.2.1.2) were disappointing. Thus is was considered necessary to investigate more time in this WP to work on WRF scalability as it was the main model used in HiRmod.

First steps were literature-based research on studies using complicated nested set-ups. This led us to contact Prof. Don Morton (Arctic Region Supercomputing Center, University of Alaska Fairbanks) who had published work on WRF benchmarks (Morton et al. 2009, 2010). He developed a challenging benchmark suite over Alaska used by the United States Department of Defense (DoD) and the U.S. National Science Foundation. This benchmark is a required benchmark for supercomputer procurement by DoD. He is as well one of the users of WRF testing new developments from the computational perspective and tightly collaborates with the U.S. National Center of Atmospheric Research (NCAR) and the U.S. weather service, National Oceanic and Atmospheric Administration (NOAA). This led to some insight into the computational problems as well as fruitful collaboration with ARSC.

A new benchmark suite, based on Morton's work, was developed in HiRmod aimed at being a representative benchmark for the climate community and focused on the needs of HiRmod. This suite contains two setups (Table 8.2.2.1, Figure 8.2.1.3) with different complexity. The European suite uses three or four nested domains and 40 or, respectively, 63 vertical levels. The domains were centred around Austria, covering either Austria (four domains) or the Greater Alpine Region (GAR, REF Auer+Böhm, three domains) with a horizontal resolution of 0.8 km (Figure 8.2.1.3). These different configurations were used with increasing core numbers on different platforms, including VSC and three supercomputers in the United States, Pacman, Kraken and Chugach (for details on the different platforms see Annex 8.1 and Arnold et al. 2011 and 2012)

The benchmark performance on the different platforms was evaluated using the metrics obtained with self-developed python scripts[2] including *wall-clock time*, *speed-up*, *efficiency, I/O time* and *integration time* as defined in the webpage and in the Annex 8.2, Sect. 8.2.1. An important point here is the separation of I/O time and integration (calculations properly) time. Results were presented in Arnold et al. 2011 and 2012 and are being prepared for a peer-reviewed publication. The scalability efficiency curves (Figure 8.2.1.4) for the VSC runs show a similar behavior as the other clusters, whereby total wall time, which includes I/O, tends to flatten out a bit more rapidly than the integration wall time. This indicates that for large problem sizes, I/O operations may take longer than the actual computations. The

[2] freely downloadable from `http://weather.arsc.edu/WRFBenchmarking/EvalTools.html`

relatively new and not intensely used Chugach presents fairly stable performance (Figure 8.2.1.6), in agreement with previous studies performed by the Arctic Region Computer Center (ARSC) on other Cray machines (Morton et al., 2009). Up to 2048 cores were used and, again, there appears to be a plateau with respect to the total wall-clock performance, reflecting the increasing I/O time. Performance on Pacman and Kraken (Figure 8.2.1.5 and Figure 8.2.1.7) tends to be somewhat irregular and more dominated by I/O costs. Of particular interest is the large and demanding *3dhrlev* case on Kraken. The I/O costs are very high in this case, yet when considering only integration time there is still reasonable scalability. The irregular behavior, such as the superlinear speedup for the *3dhrlev* case in the VSC (Figure 8.2.1.4) and almost all cases in Kraken and some in Pacman are due to the varying load conditions of the machine including the file systems. Such variations are normal in computing clusters and would require performing the benchmark several times to get averaged performance curves, with the time and computational resources.

One of the outcomes of more interest for those aiming at these sort of WRF configurations is that the scalability does not seem to suffer even though with the 3:1 nesting ratio, child nests will incur three times the number of time-steps than their parent nest. Though more rigorous analysis is warranted, it appears that the time required to integrate a particular nest is small compared to the time required for its child nest. An inspection of the simulations reveals that most of the integration time is actually spent in the innermost nest so that possible inefficiencies with respect to the outer nests (such as small chunks of the grid for each core) have no dominant influence on the overall scalability. Still – and this was encountered in some the runs with large numbers of tasks – with a large number of cores over-decomposition may occur, whereby individual tasks simply do not have enough grid points to work with (with halo points for communications, WRF requires each task to have some certain number of grid points), and then the process crashes.

The major conclusions from this WP are:

– There is a strong platform and compiler dependence. There is no guarantee for a particular hardware-software combination to work.
– Over-decomposition of the domains may be an issue. This being avoided, the integration part of WRF scales well. In order to get an optimum scaling with reasonable computation-to-communication ratio, a minimum 15 x 15 grid cells per processor should be used (in the innermost domain). If the number of grid cells per processor is too small, the decrease of integration time is not compensated by the increase in inter-processor communication time.
– Without additional modifications to the code currently a factor of approximately 1:1 between simulated time and wall-clock time is possible with 384 processors for our target setup. At least two orders of magnitude improvement would be needed for climate runs at high resolution to be able to perform simulations in a reasonable amount of time, e.g. to simulate 150 years in less than one year. Solving the I/O issues of WRF, a speedup by a factor of 5 to 10 could be obtained moving from 384 to 4000 cores.
– Good scaling is lost by the I/O time when many cores are used. This is due to the typical scatter-gather paradigm in which task 0 is in charge of reading the input, scatters the tasks among processors and gathering back their output, finally writing it out to files (Figure 8.2.1.8). There are

several options that would allow to overcome the I/O problems (some are discussed in Porter et al., 2010, and Li et al., 2003), in addition to the obvious measure of reduction of the amount of output through the introduction of more switches and internal postprocessing options into the WRF code:

a. Direct task I/O: each task reads and/or writes only the data in its subdomain. This has been tested at ARSC. They concluded that the I/O time is decreased but the large number of output files (proportional to the number of cores) makes it useless when post-processing is needed.
b. Parallel NetCDF, a software for shared, parallel access to input and output files. This is currently implemented in the newest versions of WRF but not extensively tested since special libraries are needed. ARSC is currently testing its performance.
c. Asynchronous output with so-called quilting servers: a number of tasks are reserved solely for I/O operations. This promising option, a new feature in WRF, has been tested within HiRmod. Defining the appropriate number of servers needs a benchmark itself and is case-dependant. In our tests at ARSC, the jobs would hang up. At the VSC, the same behaviour was found. However, this option could be interesting for the future and together with ARSC and WRF developers we working on this.

– Options for the required further speed-up would be:

a. A new generation of chips increasing the speed-up by a factor of 2 to 4. IBM's Powerchip 7 looks like a promising option. It was not released at the time of the project and no access to such machines existed. Note that many supercomputers dedicated for meteorological applications are based today on the Powerchip.
b. An in-depth modification of the model numerics.

A concluding remark of this work package is that, as stated above, the joint ARSC and BOKU-Met benchmarking activities started during HiRmod have evolved towards a new user-oriented benchmark suite with a webpage hosted at ARSC[3]. Two WRF benchmark cases, one with a single high-resolution domain for Alaska (official DoD benchmark), and one with a multi-domain nested configuration (with three different domain configurations options) centred on the Alps, are available. In addition, evaluation tools for comparison with timings provided on the webpage are provided. Results of benchmark users shall be published.

3.4.1.2 Highlights

The main highlight is the clarification of the role of I/O in the scalability and the related development of a new benchmark suite.

Implementation of WRF in different platforms and acquiring in depth knowledge of the main performance issues, constraints and problematic areas from a computational perspective.

---

[3] `http://weather.arsc.edu/WRFBenchmarking/`

Evaluation of the benchmark results in different platforms.

3.4.2 WP 2 Input and observational data

A selection of representative weather situations for each of our three regions of interest (ROIs: Vienna basin, Inn Valley, Black Forest) was carried out. Corresponding observational data, station as well as remote sensing data for the selected episodes were collected and used for evaluating the models performance.

3.4.2.1 Results

The simulation episodes were selected considering experiences in preceding projects (BFS, Alpnap, Bioeth) at our institute. Two episodes (see Table 8.2.2.1) per region were selected.

For the high-resolution 3-month run (see WP 4), Autumn 1999 was selected, with simulations from 20 August to 01 December. This episode was chosen as it is included in the MAP Special Observing Period (SOP) (Bougeault et al., 2001), where two of the three ROIs (the Brenner/Innsbruck region and the Rhine Valley region) are included in the innermost domain. During this SOP many data sets were collected and can be used for model evaluation. In addition, many regional climate simulation studies have this episode included in the hindcast runs and the control runs, e.g. in the ENSEMBLES project and the reclip:century project. At our institute, this year was used as a test year in two other projects, reclip:more4 and CECILIA. Climatologically, this episode contains one of the warmest September within the previous 50 years, and a slightly too cool November with above-normal amount of snow.

Meteorological data have been collected for key stations in all three ROIs. Important stations used for comparison with observations are (mountain stations are marked with ^):

- **Inn Valley:** Innsbruck University and Airport, ^Patscherkofel, Jenbach, Reutte, ^Pitztal Gletscher.
- **Vienna Basin:** Hohe Warte, Innere Stadt, Donaufeld, Wien-Flughafen.
- **Schauinsland:** ^Schauinsland, Freiburg, ^Feldberg.

Additional data, including radiosonde data in or close to the ROIs, e.g. Wien Hohe Warte and Innsbruck Airport, were collected for comparing the model performance in the free atmosphere.

Gridded observations, if available, were used. The INCA (Integrated Nowcasting through Comprehensive Analysis, `http://www.zamg.ac.at/forschung/synoptik/inca/`) gridded observation data set, developed by Zentralanstalt für Meteorologie und Geodynamik (ZAMG), was used in this study. These data are available at 1 km spatial and 1 h temporal resolutions for 2 m temperature, precipitation 10 m wind speed and direction, 2 m dew point temperature, and global radiation. For most of the episodes, except for the three-month simulation, these data are available at our institute and have been used for comparison with simulation results (see Figure 8.2.2.1 top right).

Freely available *post-processing* tools have been evaluated regarding their possible use within this project. Plotting model output, spatially, was mainly with the NCAR Command Language, NCL. In

---

[4] `http://foresight.ait.ac.at/SE/projects/reclip/results/PJ1/report5_Sensitivitaetstests_Validierung_BOKU-met.pdf`

addition, a set of shell scripts using NCL for retrieval of corresponding station points of the model input / output fields and gnuplot for plotting time series was written. Evaluation of the scores of the models was done using NCL scripts available from another project at BOKU-Met (reclip:century). As NCL is also able to read the hdf file format, comparison plots with different kinds of satellite data could also be done with NCL.

Remote sensing products were considered for model evaluation and initialisation of model runs (see original proposal). Therefore, available products for snow, temperature, and albedo were fetched and evaluated (see also intermediate report). Comparisons between 2 m temperature observations, station data as well as gridded data from INCA and model output as well as the LST (Land Surface Temperature) parameter of the MODIS satellite were carried out. For this purpose, the MODIS LST L2 5 min swath product was selected. Only tiles available for observation times close to the full hour were used for comparison with model full hour output (see Figure 8.2.2.1 middle row). Microwave sensor-based products such as soil moisture were evaluated and discussed with the colleagues from the Institute of Photogrammetry and Remote Sensing of the Technical University of Vienna. At the moment only the upper 5 cm of soil moisture are visible in the remote sensing products and their quality and resolution is not suitable to use the data for model input or evaluation.

3.4.2.2 Highlights

Gridded observation data such as the INCA data set and the remote sensing products made available for comparison with model output.

3.4.3 WP 3 Model improvements

3.4.3.1 Results

In year 1 of the project it was decided that work would be concentrated on the MM5 follow-up model WRF. This was due to increasing delays and difficulties encountered in the implementation of the models together with the termination of the official MM5 support. Therefore, the initially planned implementation of orographic shadowing in the distributed-memory version of MM5 was abandoned after a first evaluation and analysis of the time needed for the code re-programming and the aforementioned MM5 support termination.

Currently, WRF and other mesoscale / regional climate models use static input data with a rather coarse resolution and for some parameters the information is also outdated. Especially when decreasing the horizontal grid size, it is crucial to use better resolved and up-to-date input data. Global digital elevation (DEM) and land-use data sets built into the models (GTOPO30 and USGS land use respectively) come at a resolution of 30", roughly 1 km. As HiRmod focuses on horizontal resolutions of 1 km or better, it was planned to implement data sets with higher resolution: the SRTM 3" digital elevation data[5], and the CORINE Land Cover (CLC) with 100 m resolution (EEA, 2004).

[5] http://SRTM.csi.cgiar.org/

Following Pineda et al. (2004), the 44 CLC categories were remapped to the 24 USGS categories. This was necessary for being able to use the default tabulated surface parameters such as heat capacity, moisture properties, albedo, roughness etc. Although this does not take advantage of all the information in the CLC, it is still a major improvement because of the better spatial resolution, the higher accuracy, and because the CORINE land-use data are more recent. The remapping was done using ESRI ArcGIS tools and a C code for conversion into the binary format of the WRF pre-processor WPS. A detailed description of the remapping procedure and the implementation procedure into the WPS pre-processor of WRF can be found in Arnold et al. (2011) and was also posted to the WRF-forum for general use. An evaluation of the difference between built-in land-use data and the new CLC 06 data showed that (Figure 3.4.3.1) for the Vienna basin 39 % and for the Inn Valley basin even 73.5 % of the pixels differ. Side-by-side comparison of the regions shows that especially for the mountainous regions the update improved the representation of the prevailing land-use.

Two case studies on the impact of the improved land-use data were made, one for the Inn Valley and the other for the Vienna basin. WRF also comes with another, more up-to-date land-use data set, the MODIS land-cover classification (MOD12Q1), a classification carried out within the International Geosphere-Biosphere Programme. It is based on data from the MODIS sensor onboard of the Terra satellite and globally available with 1 km resolution. In contrast to the USGS data, MODIS land-cover consists of only 20 land-use classes. To quantify the differences between the two built-in land-use data and the updated CLC06-2-USGS data also the MODIS data was used (see Figure 3.4.3.1). As can be seen in the Inn Valley case, for some observation sites all data sets (USGS, CLC06, MODIS) use pixel classifications which do not represent reality, e.g. Reutte (see Figure 8.2.3.1, left), or are outdated in the USGS data, e.g. Pitztal Gletscher (see Figure 8.2.3.1, right). In general, results show improvements for most of the stations especially in specific humidity (Schicker et al., 2011a, Schicker et al., 2011b). The poster presented at the ICAM 2011 conference, shows differences between reality as seen by Google satellite images and model land-use at the observation sites. Especially for the station Pitztal Gletscher this comparison proves that the USGS classification as “glacier” for that grid box is outdated. For Patscherkofel, the USGS and the CLC00 data misclassify the terrain as “evergreen needle forest” (USGS) or “barren or sparsely vegetated” (CLC00). In the CLC06 data, it is classified closer to reality as “grassland”. Full usage of the 44 land-use classes of the CORINE data set together with the related soil parameters (soil moisture content, thermal inertia, etc.) would be desirable. In addition, not only the in-built land-use data is outdated and rather coarse, but also the built-in soil texture information with a resolution of only 2’ (about 3 km) should be replaced, as all soil parameters calculated by the models are influenced by these static soil data.

Implementing better resolved DEM data into the WRF system follows the same procedure as with the land-use data. For the comparison of GTOPO and SRTM 3″ a slightly different setup compared to the land-use data evaluation was used as we wanted to evaluate also the effects of using higher resolutions than 0.8 km. Therefore, a five-domain setup was chosen. The Inn Valley ROI was used here as it represents the most complex area. Using the higher resolved DEM (SRTM 3″) gives higher maxima and lower minima since orographic features are less smoothed. The RMSE between GTOPO and SRTM 3″ is exceeding 100 m even at a model resolution of 2.4 km (Table 8.2.3.1) which would indicate that the

SRTM 3″ data represent reality better. However, the differences between the two DEMs are systematically influenced by slope azimuths (Figure 3.4.3.2). This may indicate a problem in the SRTM 3″ data related to the radar beam incidence angle.

Several kinds of improvements for the initialisation of the model runs were considered:

1. Gridded remote sensing data (e.g. snow cover) can only be taken as mean over several observation times (8-day mean, monthly mean) due to cloud cover or observation time (e.g. night-time observations). At present, existing remote sensing derived soil moisture data have a rather coarse resolution of 25 km with limited quality, describing only the upper 5 cm of soil. Thus, they were not considered in this study.

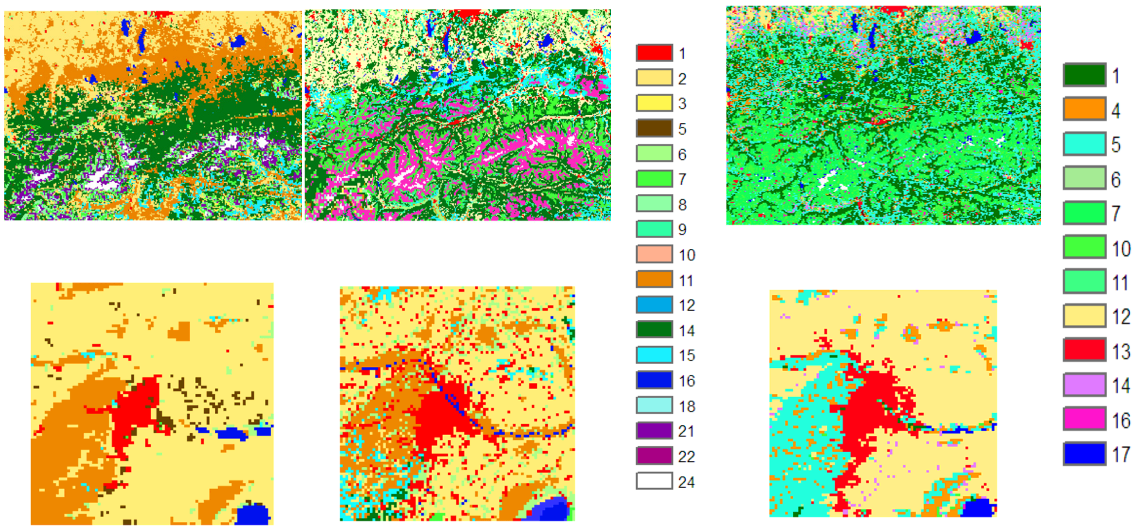


Figure 3.4.3.1: Land-use categories for the innermost domains (0.8 km grid resolution) of two ROIs: the Inn Valley (top row) and the Vienna basin (bottom row). Left column: USGS (default), middle column: CLC2006 reclassified to USGS classes, right column: MODIS. Corresponding land-use classes are plotted with similar colours, e.g. red for urban, dark blue for water bodies, etc. A detailed description of the different classes is given in the Annex (see Table 8.2.3.1).

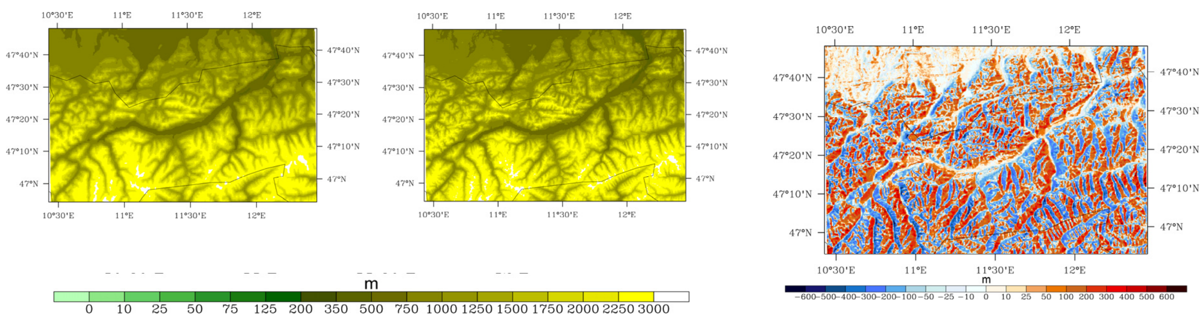


Figure 3.4.3.2: Elevation for domain 5 (0.27 km grid cell size) with the default GTOPO30 data (left), the SRTM 3″ data (middle), and the difference between the coarse and fine resolved terrain input data (right).

2. Downscaling of the temperature of the outer nest to the inner nest using a climatological value is common in meteorological models resulting often in too warm temperatures in the innermost nest. Together with the WRF model developers an optimisation was sought concluding that this change model initialisation would need more time and effort than foreseen within this project. Therefore, it is planned as a major part in the follow-up project, HiRmod-2, in close collaboration with the model developers at NCAR.
3. Model initialisation using the HRLDAS tool was considered. The problem of this method is the need for highly resolved gridded input data. When moving to the high resolution climate simulations providing enough soil spin-up it would probably be an easier solution.
4. Initialisation using ensemble data assimilation based on previous forecasts as applied in operational weather forecasting can be used to improve the soil parameters. For episodic simulations, this approach is too costly.

During the work with the different kinds of initialisation of simulations an additional question arose, on how to drive climate study hindcast simulations. Prospective climate simulations can be considered as a forecast whereas hindcast simulations are usually driven by re-analysis data, which are constrained by observation data. This is not equivalent to a free running model. If hindcast simulations just aim at producing a downscaled reanalysis, it is fine to use the best reanalysis data as boundary conditions. However, if the hindcast simulations are to be used to assess the quality of that can be expected from this method, or to assess model setups like the size of the simulation domain, what should be used? To quantify this "re-analysis" effect an episodic study was carried out starting on August 11 at 12 UTC and ending on August 17 2005 12 UTC (see Annex 8.2.3 for a detailed description).

To quantify the differences we used different kinds of input data (see Figure 8.2.3.2):

- ERA-Interim re-analysis fields (**EIRE**): six-hourly input on the original 0.75° grid.
- ERA-Interim forecast (**EIFC**): 60 and 72 forecast hours on the original 0.75° grid.
- ECMWF operational forecast (OpFC): two versions were tested, one using similar to the EIFC run the 60 and 72 forecast hours (**Op12**), and one using the 66 and 72 forecast hours (**OpFC**). For both versions the data was retrieved on a 0.75° grid.

WRF results of the four runs were compared with observations of the site Innsbruck Airport. As expected, EIRE performs best but as already mentioned before, these data are "biased" by observations. The performance of the ECMWF operational forecast with 6-hourly input is close to the performance of the ERA Interim reanalysis. Statistics given in Table 8.2.3.3 show that OpFC and EIRE perform best. It is therefore suggested to use such types of boundary conditions for the evaluation of different model setups.

In our work with MM5, the so-called truly horizontal diffusion option proved to be a key for realistic results in complex topography (Schicker and Seibert, 2009), inter alia for maintaining and developing inversions in valleys. During the project duration, the implementation of the truly horizontal diffusion in WRF was not numerically stable and let the model crash. After several tests, in coordination with the NCAR developers, this option was abandoned. However, comparing results of WRF with results of previous MM5 simulations, it was found that even with standard diffusion WRF runs perform not worse than MM5 with because of a different implementation (lower order) of the diffusion operator in WRF, which is less affected by sloped model layers.

3.4.3.2 Highlights

The re-classified CORINE land use data represent a substantial improvement. Wrong and / or outdated classification of the original USGS could be changed to be closer to reality. Updating of the land-use information resulted in improved simulation resulted at most of the stations considered for evaluation.

A new possibility for performing RCM tests with hindcast data, based on forecasts instead of analyses, has been tested and show to provide useful results. This should enable better testing of model setup and modifications in the future.

3.4.4 Work package 4: Assessment and comparison

3.4.4.1 Results

The test episodes for evaluation of model improvements were selected in WP 2 in accordance with the ROIs and desired weather situations. In WP 4, different setups of horizontal and vertical resolution as well as domain sizes have been tested to find the best simulation setup for our three regions. Furthermore, physical parameterisations have been investigated based on parameterisations used in the WRF predecessor MM5. A general setup (see Section 5), which suits best our requirements of complex terrain, was selected. Results of the simulations with this setup were presented at international conferences (attached in Annex **Error! Reference source not found.**).

A good trade off between horizontal and vertical resolution (Persson and Warner, 1991) is required, and one needs to take the computational costs of such runs into account. Having a reasonable number of vertical layers, especially in mountainous terrain and inside valleys, can improve model results but this also results in higher computational requirements (CPU time spent and storage). Simulations for the Schauinsland ROI showed slight improvements when moving from 40 vertical layers to 60 (see Figure 8.2.4.1). Still, the gain from the additional 20 layers is not as high as anticipated for this area. Also, the setup of the vertical layers, density and distance between the layers, can cause instabilities in the simulations. If the vertical spacing is too tight in the lower 100 m, especially in complex terrain, instabilities can results even using a computational time step of 1 s or less. Unaffordably short time steps would be needed to prevent eventual crashing of the simulation. Thus it was decided to use 40 vertical layers for the following simulations.

The topic nudging versus no nudging of the simulations was widely discussed within the group and with the external experts. The conclusion drawn was that for climate simulations nudging is not desired. For case / episodic and studies were the meteorological output is used as input for other models, e.g. air quality and hydrology models it should be considered.

Another topic discussed with the external experts was 1-way versus 2-way nesting interaction. A serious evaluation would require tests on different meteorological situations which was not feasible within this project. Following the advice of the experts and according to our own experiences, a 1-way online nesting technique was chosen. This technique allows to feed the innermost domain at each computational step but without feedback to the mother domain from the nested fields. It is much superior to 1-way *off-line* nesting where information would be passed only at each output time step.

In complex terrain, when slopes become steeper, meteorological models start having problems caused by numerical problems. A simple and limited workaround is to smoothen the underlying topography. In HiRmod, the default smoothing as applied in the WRF pre-processor WPS was used. Furthermore, the numerical scheme was slightly tuned towards a more implicit integration of vertical diffusion, following the advice of developers.

The implementation of the remapped CLC land-use data was evaluated in two ROIs, the Vienna basin and the Inn Valley. In total, eight runs have been carried out (see Table 8.2.4.2). Simulations for the Vienna basin were set up with a domain layout used in an other study (BioETH) where MM5 was used. This was done to also compare the skills of MM5 and WRF for that region. For the Inn Valley, a four domain setup was chosen with the innermost domain as large as possible to avoid cutting through important terrain structures (see Figure 3.4.3.1 top). In both ROIs, 0.8 km resolution was used in the innermost domain. The physical parameterisations used are summarised in Table 8.2.1.1.

For the Vienna basin runs (see Figure 8.2.4.2 for results of selected stations) an additional test was carried out with the urban parameterisation of WRF, which has an urban model coupled to the WRF model. This was done as the Vienna basin is a densely populated region and a large fraction of the modelling domain is classified as urban area. For the Inn Valley domain, a test using the CLC00 data was carried out. By the time of this work the CLC06 data was still not fully available, e.g. Switzerland and Great Britain were missing. Results of the Inn Valley runs (see Figure 8.2.4.3 for results of selected stations) show for most of the target region an improvement with the recent land-use data. Significant differences caused by land-use changes in the temperature and specific humidity can be seen as well as improved temperature maxima. Minimum temperatures being underestimated in the simulations with the original USGS data are not improved. Especially at the sites Patscherkofel and Pitztal Gletscher the new land-use information improves the simulation results. Results for the site Reutte, on the other hand, show that applying the class “urban” to a more suburban type of land with sparse buildings leads to a dry bias. Simple reclassification of the data is thus not an ideal way. Results for the Vienna basin show that here the daily maxima are not captured but that daily minima are well represented for the selected stations. The simulation results of non-urban compared to urban USGS runs show a bigger difference than using different land-use schemes with the urban scheme applied. With the updated land-use data, spatial patterns of surface temperature agree better with the MODIS data than the old and outdated USGS land-use data and thus represent reality better. In general, one can conclude that the new land-use information improves simulation results for complex terrain areas but for hilly and flat terrain, especially when most of the domain is covered by the urban class, the main changes at the station points are related to the change in urban – non-urban scheme. A full usage of the CORINE land-use data set would be desirable but this also needs the collection of the necessary surface parameters as roughness length, emissivity, albedo, etc.

As pointed out already, the time is not yet ripe for long-term climate simulations at the km-scale. For comparison with the results of standard RCM simulations, a three-month time slice run was set up. Autumn 1999 was selected (see Sect. 3.4.2) for this period. Evaluations of the computational costs of different domain setups led to the conclusion that such a time slice simulation is only feasible when centring the innermost domain around Austria with as few surrounding grid points as possible (see Figure 8.2.4.4). Still, estimation of the needed time and, most of all, storage needs of such a run showed that a climate simulation using 0.8 km in the innermost nest is not possible within the amount of time one usually has (~1 year pure calculation time for 200 years of simulation) for such regional climate simulations. The episode simulated here consist of 102 days of simulation which will take 115 days of pure calculation time. The storage needs for such a three-month time slice simulation are roughly 6.7 TB, for all four used domains with standard (not postprocessed or reduced) model output.

A very preliminary comparison of the first five weeks of the three-month run for daily mean, minimum and maximum temperatures at station Innsbruck-University (see Figures 2.5.3.5.5 and 2.5.3.5.6) shows a relatively large bias at the beginning of the simulation, possibly attributable to spinup, but also later the deviations are on the order of several degrees. At this point in time, it is premature to give a general assessment on the quality of the simulation or explanations for deviations. Comparisons with RCM results (reclip:century) were not possible in the time frame of the project. Still, the produced data sets will be made freely available for further investigation.

3.4.4.2 Highlights

Improvement of the land-use data with remapped CORINE CLC06 data showed in general improvements of the model simulations.

Tests showed that 40 vertical levels are sufficient, making long-term simulations easier.

3.4.5 Work package 5: Application to dispersion modelling

3.4.5.1 Results

This part was originally scheduled towards the end of the project. However, as during the implementation of the meteorological models there was some time available while waiting for turnaround of jobs, it was decided to already start with the implementation of the dispersion model (FLEXPART) with its versions for MM5 and WRF in different Linux systems and in the VSC. For the MM5 version, developed at BOKU-Met, compiler- and platform- specific issues were found. However, as it was decided at some to switch solely to WRF, this was not investigated further. The WRF version available was from another group and had not compile or runtime issues. However, it was not mature and existed in three different versions released unofficially, each of them with other issues that would need to be addressed. Considering the delay experienced in WP1 and the amount of work in the other WPs, it was decided to not continue work in this work package. This decision was fully supported by the group of external experts.

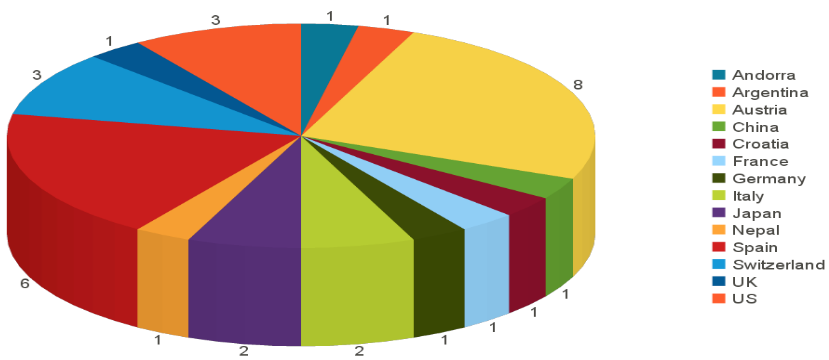
3.4.6 Work package 6: Management

3.4.6.1 Results

A ticket system and internal wiki has been created for the HiRmod project with the free trac software[6]. This has allowed a nice organisation of the tasks and coordination of the work. Several team meetings were held and reported in the ticket system.

As scheduled, one workshop with the external experts was held in Vienna on the 1st and 2nd of February 2010. A second workshop with the group of external experts was held on the 25th of January 2011.

In January 2011 contact to Don Morton of the Arctic Region Supercomputing Center (ARSC) was established due to surprising results of the WRF benchmark test. This contact grew towards an informal collaboration and small studies were carried out together on high resolution modelling in complex topography in the Juneau area (Harrison et al., 2011a, 2011b, Morton et al., 2011). These studies were performed together with an undergraduate student who was awarded the first price at the student presentation competition at the Alaska Weather symposium. This collaboration tightened and the idea of hosting a co-organised workshop on high resolution modelling in complex terrain (HiRCoT) in Vienna appeared. The HiRCoT workshop (`met.boku.ac.at/hircotwiki/`) then started to develop and a well-attended and productive three-day workshop took place in Vienna in February 2012. This workshop was different compared to other conferences as it was based solely on interactive discussions triggered by an introduction given by a designated participant and moderated by one of the HiRmod team members. The organisation of the workshop was shared between BOKU-Met, ARSC, and the Institute of Meteorology and Geophysics of the University of Innsbruck. The latter brought in the WWRP (the World Weather Research Program) through its working group on Mesoscale Weather Forecast Research (WG MWFR), which funded some of the participants. The workshop included also pre- and post-workshop activities. A wiki page was set up for initial discussion and planning and to post the workshop outcome. In addition to the wiki, the organisers are gathering a joint report that will be made public. It is important to highlight that the workshop included 32 participants from more than 13 different countries (Figure 3.4.6.1) and that all the participants congratulated the organisers for the idea and the workshop itself and agreed on a follow-up workshop in two to three years.



6 Trac is a web-based software project management and bug/issue tracking system. It provides an integrated Wiki. It is based on python. For details and downloads, see the Trac open source project home page at `http://trac.edgewall.org/`

Figure 3.4.6.1.: Country distribution of the HiRCot participants.

4 Conclusions and recommendations

4.1 Which findings have been derived from the project by the project team?

The results of our simulations confirm that at very high resolution (~ 1 km) climate simulations are desirable because the meteorological phenomena are better represented. However, the currently available models are not yet ready for the length and computational demands such simulations need. On the Vienna Scientific Cluster (VSC-1), we can simulate 1 month of real time in 1 month of wall-clock time in a realistic setup, thus, only runs for a few months are feasible. For climate applications, a speed-up by two orders of magnitude will be necessary. Then it would be possible, for example, to do a 30-year run in about 4 months. Our detailed findings from real-case WRF benchmark runs are:

1. The pure model integration part of WRF scales well with the number of processor cores and would allow the use of thousands of cores.
2. However, I/O operations (and this means mainly output) constitute a severe performance bottleneck, both in terms of time spent on I/O and amount of output. The first priority obviously is to reduce the amount of output, as this will at the same time also reduce the I/O time. For the required order of improvement of scalability, it will be necessary in addition to move from the default scatter/gather implementation, where one task is in charge of gathering and distributing the information to and from the various compute nodes as well as sending the output to mass storage to alternative approaches. Possible approaches are so-called quilting (where one node collects information from a group of others) and parallel file systems, possibly supported by parallel application software such as pnetCDF. Even direct I/O from each node might be considered.
3. All these possibilities are already available and would probably allow increase of the speed by a factor 5 to 10, e.g. with going from presently-used 384 cores to 4096 cores. As far as can be judged at the moment, this will, however, not be sufficient for the final goal. A speedup through optimised numerical and physical schemes of the model as well as improved scalar performance (faster CPUs) has to be envisaged. In this respect, it should be noted that most meteorological HPC centres rely on IBM's Power Chip © architecture which is considerably faster than the Intel © and AMD © processors used in general-purpose HPC facilities including VSC-1 and VSC-2.

Apart from the output limitation discussed above, working with large domains is not problematic at all. This is very good news since the target regions should be sufficiently far from the domain boundaries while being large enough not to cut through important orographic features. For example, it would be desirable to include the whole Alps into the innermost domain. In addition to this, each task (core) needs a minimum of 15x15 grid cells in order to have a reasonable computation to communication ratio. This latter condition implies that a relatively large innermost domain (about 10^6 horizontal grid cells) is actually desirable.

The land-use and elevation data built into MM5 and WRF models have been replaced by SRTM 3" elevation data and CORINE CLC2006 land-use data with 100 m resolution. The CORINE land-use classes were remapped to the 24 classes used in the default USGS land-use data set. The differences in the land-use are partially substantial. This generally lead to improvements of simulated 2 m temperatures and relative humidity values.

However, one should not take the data without detailed inspection since:

1. Satellite elevation data is not perfect and may present shifts which are significant at resolutions below 1 km. At 1 km resolution or more coarse resolutions one can use the default GTOPO30 data (~ 1 km). However, when moving towards higher resolutions the ASTER GDEM 1" or SRTM 3" data should be considered.
2. In some areas, misclassification of land-use in the USGS land-use data set has been found. However, also in other land-use data sets some regions can show differences between reality and the data sets. These differences can be products of the processing procedure of the satellite data used for generating these data sets. We do not think that such data are perfect. Still, it is desirable to use the most up-to-date and best resolved data sets. Thus, an evaluation of the data before using should be carried out.

In order to make full use of the high-quality CORINE land-use data set, in the future, surface and soil parameters for all the 44 land-use classes available in CLC2006 should be collected and implemented. Also some other parameters related to surface processes, most notably the soil texture and soil depth, should be improved.

Nudging is not desired for climate runs and should be considered only in episodic studies and studies were the meteorological output is used as input for other models, e.g. air quality and hydrology models.

There exist no conclusive and comprehensive work and outcome of this and other studies on 1-way versus 2-way nesting interaction. A proper evaluation would require tests on hundreds of different meteorological situations and this was not feasible in this project. However, this issue was discussed with several experienced scientists. Following their advice and according to our own experiences, a 1-way online nesting technique was chosen. This technique allows to feed the innermost domain at each computational step (not output time step, which represents the typical 1-way off-line nesting procedure) but without forcing the mother domain with the nested fields.

Advection of TKE is needed but was not officially implemented in WRF until the last version (released at the end of the project). At high resolutions. thus small grid sizes, horizontal advection of the TKE starts being important. Most of the boundary layer (BL) schemes implemented in Numerical Weather Prediction (NWP) models only vertical mixing and no horizontal advection is considered the boundary layer. At very high resolutions eddies start being resolved and simulations get closer to the Large Eddy Simulation (LES) realm. However, LES is still not a solution for complex topography due to initialisation and boundary condition problems. Therefore, alternative solutions are needed. By the end of the HiRmod project, the WRF community had implemented one BL parameterisation allowing the full prognostic of TKE, thus advecting the TKE without explicitly resolving the eddies.

Initial conditions of the atmospheric and also of the soil parameters are crucial for episodic simulations. In weather forecasting, ensemble data assimilation can be used to improve these parameters on the background of the previous forecast. For episodic simulations, this problem is not easily solved. In climate simulations including time-slice runs, enough time for spin-up of the soil parameters needs to be provided, either with long spin-ups of the model themselves or by running first a less expensive off-line surface model for the appropriate number of years.

Forecasts used as IC and BC for episodic runs seem to be a useful approach to perform episodic runs to be compared with climate runs. Further development in this direction is needed.

4.2 Which further steps will be taken by the project team on the basis of the results obtained?

The results obtained in HiRmod and HiRCoT has allowed us to settle the key lines that scientists need to address in this topics. We have established strong tights with the community, and, most importantly, with the model developers, who have agreed to collaborate with us in a following up project. It is expected to submit a HiRmod2 proposal in the next ACRP call in order to address some of the issues identified in HiRmod, specially focussing on the soil properties and data on one hand, and model initialisation on the other.

The collaborations with ARSC will continue for the Juneau case studies and to push the models at higher resolution using TKE advective schemes. This will be at an informal level due to the changes in the job positions of the HiRmod team members.

The approach of using reanalysis versus forecast input as driving data for future climate simulations did show interesting results. Evaluation and results of these simulation runs will be used for a publication.

The results and knowledge gained of the still ongoing long run will be further distributed and comparison with existing observation data will be carried out. Furthermore, especially the knowledge gained from simulation length and output storage needs will be discussed with the modelling community. For climate applications additional parameters need to be included into the model output and the general storage needs need to be reduced to a reasonable amount either by direct namelist switches for the model itself or by additional post-processing steps. It is planned to submit another publication dealing with the results of the long run.

4.3 Which other target groups can draw relevant and interesting conclusions from the project results and who can continue working on that basis?

The work and results here presented are of relevance to all the communities that use high-resolution meteorological modelling.

Meteorological services of Alpine countries are presently moving towards a 1 km grid spacing with their operational forecast models, the resolution studied in HiRmod. Here they encounter the same problems and all the experiences and conclusions are of direct relevance..

Impact modellers, e.g. hydrologists, air quality modellers will be able to use the output of the three-month run for testing their models with fully dynamically generated input data at 0.8 km resolution.

Climate scientists responsible for shaping future directions of downscaling in complex terrain can get insight on the present and near-future potentials and limitations of dynamical downscaling with nonhydrostatic meteorological models.

International contacts and collaborations have been established, and the collaboration partners benefit from the work and results of HiRmod. This informal network includes:

1. Model developers (WRF – both NCAR and NCEP/NOAA, ICON at DWD and COSMO at Meteoswiss)
2. Forecast offices and meteorological centres (ZAMG, Alaska NOAA forecast office, Catalan Meteorological Service, Croatian Meteorological Service, Andorra Meteorological Service, DWD)
3. Supercomputing facilities with weather research interests (ARSC, BSC, VSC)
4. Universities (University of Wien, University of Alaska Fairbanks, ETH Zurich, University of Zagreb, Technical University of Catalonia, TU Wien, ISAC Torino, University of Alaska Fairbanks)

References

Arnold D., I. Schicker, P. Seibert (2010): High-Resolution Atmospheric Modelling in Complex Terrain for Future Climate Simulations (HiRmod) - Report 2010. Vienna Scientific Cluster (VSC), 8.

Arnold, D., I. Schicker, H. Formayer and P. Seibert (2010b): Towards high-resolution environmental modelling in the Alpine region. , 31st ITM - NATO/SPS International Technical Meeting on Air Pollution Modelling and its Application, 27 Sep - 01 Oct, 2010, Torino, Italy.

Arnold, Delia , Don Morton, Irene Schicker, Jan Zabloudil, Oriol Jorba, Kayla Harrison, Greg Newby, and Petra Seibert (2011): WRF benchmark for regional applications.. In: National Center for Atmospheric Research, 12th WRF Users' Workshop, Boulder, Colorado, USA, June 20 - 24, 2011http://www.mmm.ucar.edu/wrf/users/workshops/WS2011/Extended%20Abstracts%202011/P6_Arnold_ExtendedAbstract_11.pdf

Arnold. D., D. Morton, I. Schicker, O. Jorba, K. Harrison, J. Zabloudil, G. Newby, P. Seibert, 2012: Application of a real-case benchmark test of the Weather Reasearch and Forecast model WRF, User meeting Vienna Scientific Cluster, February 27.-28. 2012, Neusiedl / See.

Caya, D., and R. Laprise (1999), A Semi-Implicit Semi-Lagrangian Regional Climate Model: The Canadian RCM. Mon. Wea. Rev., 127, 341-362.

EEA (2004), Corine Land Cover 2000 - Mapping a decade of change, Brochure No 4/2004, http://www.eea.europa.eu/publications/brochure_2006_0306_103624/at_download/file (accessed 04.02.2009)

Farr, T. G., et al. (2007), The Shuttle Radar Topography Mission, Rev. Geophys., 45, RG2004, doi:10.1029/2005RG000183.

Fernández, J., J. P. Montávez, J. Sáenz, J. F. González-Rouco, and E. Zorita (2007), Sensitivity of the MM5 mesoscale model to physical parameterizations for regional climate studies: Annual cycle, J. Geophys. Res., 112, D04101, doi:10.1029/2005JD006649.

Grell G., Dudhia J. and Stauffer D (1994), A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5), NCAR/TN-398+STR, (http://www.mmm.ucar.edu/mm5/documents/mm5-desc-doc.html)

Harrison, K., Morton D., Zavodsky B., Chou S.H. (2010)"Assessment of data assimilation with the Protoype High Resolution Rapid Refresh for Alaska (HRRRAK)"

Harrison, K., D. Arnold, I. Schicker, D. Morton and C. Dierking (2011a): A high resolution WRF simulation of a post-frontal topographically enhanced wind shear event at Juneau International Airport. In: ARSC (Hrsg.), 2011 Alaska Weather Symposium, http://weather.arsc.edu/Events/AWS11/Abstracts/Poster_Harrison.html, The Alaska Weather Symposium, Fairbanks, Fairbanks, AK, USA, 15-16 March 2011.

Harrison, K., Delia Arnold, Irene Schicker, Don Morton, Carl Dierking (2011b): Arctic Region Supercomputing Center, University of Alaska Fairbanks, Fairbanks, Alaska, USA. In: NCAS (Hrsg.) and Met Office (Hrsg.), ICAM Poster Presentations, http://www.ncas.ac.uk/index.php?option=com_docman&task=doc_download&gid=410 ICAM - International Conference on Alpine Meteorology, Aviemore, Scotland, UK, May 23-27,2011]

Loibl, W., Beck, A., Dorninger, M., Formayer, M., Gobiet, A. and W. Schöner (Eds.) (2007) Kwiss-Programm reclip:more research for climate protection: model run evaluation, Final report, ARC-sys-0123, http://systemsresearch.arcs.ac.at/SE/projects/reclip/reports/ARC-sys-reclip_more1-3final_rep.pdf (accessed 04.02.2009)

Morton, D., O. Nudson, and C. Stephenson, "Benchmarking and Evaluation of the Weather Research and Forecasting (WRF) Model on the Cray XT5" in *Cray User Group Proceedings*, Atlanta, GA, 04-07 May 2009.

Morton, D., O. Nudson, D. Bahls, G. Newby, "Pushing WRF to Its Computational Limits," *The Alaska Weather Symposium*, Fairbanks, AK, 09-10 March 2010.

Morton, D., D. Arnold, I. Schicker, C. Dierking, K. Harrison, "Very High Resolution Numerical Prediction of Wind Shear Event in the Complex Terrain Around Juneau Alaska," in American Geophysical Union Annual Meeting, San Francisco, CA, 05-09 December 2011.

Pineda, N, Jorba, O, Jorge, J, and J. M. Baldasano (2004) Using NOAA AVHRR and SPOT VGT data to estimate surface parameters: application to a mesoscale meteorological model, Int. J. Remote Sensing, 25, 1, pp. 129-143(15).

Persson, P.O.G. and T.T. Warner (1991), Model generation of spurious gravity waves due to inconsistency of the vertical and horizontal resolution, Mon. Wea. Rev., 119, pp.917 – 935.

Schicker I, Seibert P, Mursch-Radlgruber E (2008): Investigation of observed and modelled nocturnal wind and temperature oscillations in an Alpine valley. Extended Abstract, 18th Symposium on Boundary Layers and Turbulence, 9. – 13. June 2008, Stockholm, http://ams.confex.com/ams/pdfpapers/139845.pdf. Accessed 31 July 2008.

Schicker, I. and P. Seibert (2009): Simulation of the meteorological conditions during a winter smog episode in the Inn Valley, Meteorol. Atmos. Phys., in print. Online at http://www.springerlink.com/content/g73207h7x755q280/fulltext.pdf. DOI 10.1007/s00703-008-0346-z, Accessed 17 February 2008.

Schicker I., Delia Arnold, Petra Seibert (2011a): Updating the currently available landuse data in WRF: impacts on simulations for the Austrian Inn Valley. In: NCAS (Hrsg.) and Met Office (Hrsg.), International Conference on Alpine Meteorology, Aviemore, Scotland, UK, May 23-27, 2011.

Schicker, I., Arnold, D., Morton, D., and P. Seibert (2011b): Effects of updated land-use in WRF over mountainous terrain in American Geophysical Union Annual Meeting, San Francisco, CA, 05-09 December 2011.

Schmidli, J., G.S. Poulos, M.H. Daniels, and F.K. Chow (2009), External influences on nocturnal thermally driven flows in a deep valley. J. Appl. Meteor. Climatol., 48, 3–23.

Seibert P., Skomorowski P. (2008): Untersuchung der orographischen Besonderheiten der Probennahmestellen Schauinsland und Freiburg und deren Auswirkungen auf die Genauigkeit von adjungierten atmosphärischen Ausbreitungsrechnungen. Bundesamt für Strahlenschutz, Salzgitter / Freiburg. Schriftenreihe Reaktorsicherheit und Strahlenschutz, BMU - 2008 - 713, http://www.bmu.de/strahlenschutz/schriftenreihe_reaktorsicherheit_strahlenschutz/doc/41875.php , 194 pp.

Simmons A, Uppala S, Dee D, Kobayashi S. 2006. ERA-Interim: New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter* **110:** 26–35.

Skamarock, W. C., Klemp, J. B. , Dudhia, J., Gill, D. O., Barker, D. M., Duda, D.M., Huang, X.-Y.,. Wang, W and J. G. Powers (2008), A description of the Advanced Research WRF Version 3. NCAR Tech Notes-475+STR (http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf, accessed 13.02.2009)

Steinacker, R. (1984), Area – Height Distribution of a Valley and its Relation to the Valley Wind, Contrib Atmos Phys., 57, 1, pp 64 – 71.

Stohl, A., Forster, C., Frank, A., Seibert, P., and Wotawa, G. (2005): Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2., Atmos. Chem. Phys., 5, 2461–2474.

Stohl, A., Seibert, P., Arduini,J., Eckhardt, S., Fraser, P., Greally, B. R., Maione, M., O'Doherty, S., Prinn, R. G., Reimann, S., Saito, T., Schmidbauer, N., Simmonds, P. G., Vollmer, M. K., Weiss, R. F., and Y. Yokouchi, (2008), A new analytical inversion method for determining regional and global emissions of greenhouse gases: sensitivity studies and application to halocarbons, Atmos. Chem. Phys. Discuss., 8, pp 19063-19121. Final version for ACP is in print (2009).

Zängl, G. (2002), An Improved Method for Computing Horizontal Diffusion in a Sigma-Coordinate Model and Its Application to Simulations over Mountainous Topography. Mon. Wea. Rev., 130, 1423–1432.

Zängl, G. (2003), A Generalized Sigma-Coordinate System for the MM5. Mon. Wea. Rev., 131, 2875–2884.

Zängl, G. (2004), A reexamination of the valley wind system in the Alpine Inn Valley with numerical simulations. Meteorology and Atmospheric Physics, 87, 4, 241-256.

Zängl, G. (2007), To what extent does increased model resolution improve simulated precipitation fields? A case study of two north-Alpine heavy-rainfall events, Met. Zeit., 16, 5, pp 571-580.

C) Project details

5 Method

5.1 WP 1 Computational aspects

Complex meteorological models such as MM5 or WRF always require some work to implement them on different hardware platforms with different compilers and libraries for parallelisation. Both models are implemented on cluster environments and tested, using different compilers and compiler options with suitable benchmarks.

5.2 WP 2 Input and observational data

A careful selection of representative weather situations for each of our three regions of interest (Vienna basin, Inn valley, Black Forest) is carried out. The corresponding observation data, station as well as remote sensing data, for the selected episodes are collected for usage in evaluating the models skills. Post-processing routines are developed and adapted.

5.3 WP 3 Model improvements

Models shall be improved through higher resolved static input fields, analysing the initialisation routines, and evaluating the possibilities of recoding shared-memory code snippets of MM5 to be used in distributed-memory mode. The 100 m land use data of the CORINE CLC projects (EEA, 2004), reclassified to the USGS land use classes, and the 3" (~90 m) topographic data of the shuttle radar topography mission (SRTM, Farr et al., 2007) are implemented into the pre-processor of WRF, WPS. The ERA Interim data (Simmons et al., 2006) were mostly used as model boundary conditions.

5.4 WP 4 Assessment and comparison

Model improvements implemented in WP 3 are tested for the episodes selected in WP 2. Additional test runs analysing the influence of domain definition, vertical resolution, influence of physical schemes, and definition of the final parameterisation scheme are carried out.

5.5 WP 5 Application to dispersion modelling

The application of the Lagrangian particle dispersion model FLEXPART (Stohl et al., 2005) was initially planned as a supplementary activity in order to provide an additional mode of evaluation for the meteorological modelling, and as it is an interesting and valuable application. However, during the evolution of the project, it was decided to skip this work package (see Section 2.2), in agreement with the group of external experts accompanying the project.

5.6 WP 6 Management

The coordination of the project work-flow was done in internal meetings, by email and phone calls and a ticket system. Meetings with a group of external experts were carried out providing very important feedback to the project. Intermediate reports and final report are to be written.

6 Work and time schedule

Month Tasks	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1.1 Implementation of models																								
1.2 Computational costs																								
2.1 Selection of episodes																								
2.2 Get input fields, obs.data																								
2.3 Adaptation of postprocess.																								
2.4 Remote sensing data																								
3.1 Improved DEM & land-use																								
3.2 All codes for DM machines																								
3.3 Improved initialisation																								
4.1 Assess. of improvements																								
4.2 Assess. of domain & resol.																								
4.3 Phys schemes, longer runs																								
4.4 Comparison with RCM																								
5.1 Simulation of Rn etc.																								
5.2 Source-recept. comparison																								
6. Management																								

Grey cells correspond to the original plan (normal or low intensity of work). Red is used to denote work periods that were planned but had to be shifted in time, violet denotes work time added compared to the original plan. Normal activity is shown in dark colours, low-intensity work in light colour shade. Green denotes the work planned for WP5.

7 Publications und dissemination

Published articles and book contributions:

D. Arnold, I. Schicker, H. Formayer and P. Seibert. (2012): Towards high-resolution environmental modelling in the Alpine region. In: Steyn, Douw G., Trini Castelli, Silvia (Eds.), *Air Pollution Modeling and its Application XXI*, p. 269-272; Springer, Dordrecht; ISBN 978-94-007-1358

D. Arnold, I. Schicker, P. Seibert (2010): High-Resolution Atmospheric Modelling in Complex Terrain for Future Climate Simulations (HiRmod) - Report 2010. Vienna Scientific Cluster (VSC), 8

Articles under preparation:

I. Schicker, D. Arnold, and P. Seibert: Using reclassified Corine land-use data in WRF: Influence on simulated meteorological conditions in the Vienna basin for a summertime period. To be submitted to *Meteorology and Atmospheric Physics* in June 2012. Abstract: *The built-in USGS 24 category land-use data in WRF was compared to remapped CORINE 2006 land-use data, representing an updated and more accurate image of European land cover for a summertime episode in the Vienna basin, Austria. In addition, also simulations using the built-in MODIS 20 category land-use data. For the Vienna basin simulations were performed using also the urban scheme WRF provides. Results show in general the simulation using the CORINE data set represents more reality but the diurnal range is underestimated in all simulations.*

D. Arnold, D. Morton, I. Schicker, J. Zabloudil, O. Jorba, K. Harrison, G. Newby, and P. Seibert: A user-oriented WRF benchmark for regional climate applications. To be submitted to *Geoscientific Model Development*, in May 2012. Abstract: *Despite parallelisation, scalable performance of WRF is often not achieved. Although the WRFV3 Parallel Benchmark Page provides valuable scaling information, this one-domain configuration is often not typical of the general application of WRF to nested domains of varying sizes and shapes. This study is a first step in providing a centralised WRF performance repository for a variety of typical configurations and environments that might be found in general NWP environments. The performance of WRF V3.2.1 and V 3.3.1 is analysed in several multi-nest configurations - varying vertical levels and parameterisations - and tested for scalability on different platforms. Initial insight shows that multi-nest configurations make realization of desired scalabilities more difficult. In many real-world cases, the outer nest has substantially fewer grid points than the inner nests, and this can be problematic in that large-scale domain decomposition of the inner nests - where the great majority of computations take place - is limited by "over-decomposition" of the outer nest. In addition, I/O has been found to be a bottle-neck and different approaches and paradigm changes are investigated, from the usual master/paradigm to parallel netCDF in combination with quilting.*

I. Schicker, D. Arnold, H. Formayer, and P. Seibert: A very high resolution time slice simulation for Austria of autumn 1999. In preparation.

Conference contributions:

Arnold, D., Schicker, I., and P. Seibert (2010a): Atmospheric transport modelling in mountainous regions using very high resolution meteorological simulations. , 14th Conference on Mountain Meteorology, 30 August – 3 September, Squaw Valley, California

Arnold, D., I. Schicker, H. Formayer and P. Seibert (2010b): Towards high-resolution environmental modelling in the Alpine region. , 31st ITM - NATO/SPS International Technical Meeting on Air Pollution Modelling and its Application, 27 Sep - 01 Oct, 2010, Torino, Italy

Arnold, Delia , Don Morton, Irene Schicker, Jan Zabloudil, Oriol Jorba, Kayla Harrison, Greg Newby, and Petra Seibert (2011): WRF benchmark for regional applications.. In: National Center for Atmospheric Research, 12th WRF Users' Workshop, Boulder, Colorado, USA, June 20 - 24, 2011. http://www.mmm.ucar.edu/wrf/users/workshops/WS2011/Extended%20Abstracts%202011/P6_Arnold_ExtendedAbstract_11.pdf [Poster]

Arnold. D., D. Morton, I. Schicker, O. Jorba, K. Harrison, J. Zabloudil, G. Newby, P. Seibert, 2012: Application of a real-case benchmark test of the Weather Reasearch and Forecast model WRF, User meeting Vienna Scientific Cluster, February 27.-28. 2012, Neusiedl / See

Harrison, K., D. Arnold, I. Schicker, D. Morton and C. Dierking (2011): A high resolution WRF simulation of a post-frontal topographically enhanced wind shear event at Juneau International Airport. In: ARSC (Hrsg.), The Alaska Weather Symposium, Fairbanks, Fairbanks, AK, USA, 15-16 March 2011. http://weather.arsc.edu/Events/AWS11/Abstracts/Poster_Harrison.html [Poster]

Harrison, K., D. Arnold, I. Schicker, D. Morton and C. Dierking, "Very high-resolution WRF simulations of a wind shear event in complex terrain at Juneau, Alaska," Poster, *12th Annual WRF Users' Workshop*, Boulder, CO, 20-24 June 2011.

Harrison, K., D. Arnold, I. Schicker, D. Morton and C. Dierking, "A high resolution WRF simulation of a post-frontal topographically enhanced wind shear event at Juneau International Airport," poster, *International Conference on Alpine Meteorology*, Aviemore, Scotland, 23-27 May 2011.

Harrison, K., D. Arnold, I. Schicker, D. Morton and C. Dierking, "A high resolution WRF simulation of a post-frontal topographically enhanced wind shear event at Juneau International Airport," poster, *The Alaska Weather Symposium*, Fairbanks, AK, 15-16 March 2011.

Harrison, K., Delia Arnold, Irene Schicker, Don Morton, Carl Dierking (2011): Arctic Region Supercomputing Center, University of Alaska Fairbanks, Fairbanks, Alaska, USA. In: NCAS (Hrsg.) and Met Office (Hrsg.), International Conference on Alpine Meteorology, Aviemore, Scotland, UK, May 23-27, 2011. http://www.ncas.ac.uk/index.php?option=com_content&view=article&id=806%3Ap1j&catid=196&Itemid=338 [Poster]

Morton, D., D. Arnold, I. Schicker, C. Dierking, K. Harrison, "Very High Resolution Numerical Prediction of Wind Shear Event in the Complex Terrain Around Juneau Alaska," in *American Geophysical Union Annual Meeting*, San Francisco, CA, 05-09 December 2011.

Morton, D., D. Arnold, I. Schicker, K. Harrison, C. Dierking, and E. Petrescu, "Issues in Very High Resolution Numerical Weather Prediction over Complex Terrain in Juneau, Alaska," Poster, in *National Weather Association 36th Annual Meeting*, Birmingham, AL, 15-20 October 2011.

Morton, D., O. Nudson, D. Bahls, P. Johnsen, D. Arnold and I. Schicker, "Grand-scale WRF Testing on the Cray XT5 and XE6," in *Cray User Group Proceedings*, Fairbanks, Alaska, 23-26 May 2011.

Schicker I., Arnold D., Seibert P. (2011): The HiRmod project - preparing for regional climate modelling with high resolution non-hydrostatic models. , International Symposium Climate Change in High Mountain Regions, 29 August - 1 September 2011, SALZBURG, AUSTRIA

Schicker I., Arnold D., Seibert P. (2011): The HiRmod project - What high resolution climate simulations run into, 12. Klimatag, 21. - 22. September 2011, Vienna, Austria

Schicker, I, Arnold, D., and P. Seibert (2010): A case study of very high resolution meteorological modelling in Alpine landscapes using MM5 and WRF. , 14th Conference on Mountain Meteorology, 30 August – 3 September, Squaw Valley, CA

Schicker, I, Arnold, D., Formayer, H., and P. Seibert: A very high resolution time slice simulation of Autumn 1999 for Austria – how well does WRF perform compared to observations and the MAP SOP? 15th AMS conference on Mountain Meteorology, Steamboat Springs, Colorado, USA, August 2012

Schicker, I., Arnold, D., and Petra Seibert (2011a): Updating the currently available landuse data in WRF: impacts on simulations for the Austrian Inn Valley. In: NCAS (Hrsg.) and Met Office (Hrsg.), International Conference on Alpine Meteorology, Aviemore, Scotland, UK, May 23-27, 2011. http://icam.ncas.ac.uk/files/schicker_icam2011.pdf [Poster]

Schicker, I., Arnold, D., Morton, D., and P. Seibert (2011b): Effects of updated land-use in WRF over mountainous terrain in American Geophysical Union Annual Meeting, San Francisco, CA, 05-09 December 2011.

Petra Seibert, Dèlia Arnold, Irene Schicker (2010): High-Resolution atmospheric modelling in complex terrain for future climate applications. , KLI.EN workshop "Klimafolgenforschung – Rahmenbedingungen und Förderungen des Klima- und Energiefonds", 15 Jul 2010, Wien

Petra Seibert, Irene Schicker, Delia Arnold, Herbert Formayer, and Imran Nadeem (2010): Climate simulation in mountain regions: why we need sub-km-scale resolution. , EGU General Assembly 2010, 02 – 07 May 2010, Wien [Poster]

Invited seminar at the Meteorological Institute of the University of Zagreb and the Meteorological Service of Croatia, December 2011.

Websites:

- `http://weather.arsc.edu/WRFBenchmarking/` This website presents two benchmark suites . A snapshot is presented in Figure .
- `http://met.boku.ac.at/hircotwiki` (see Figure 7.1). This website (not yet public) has been used as a discussion for the creation of the HiRCoT2012 workshop and as a platform of communication between the participants. It includes a discussion section, reports and references.

Figure 7.1: Snapshot of the benchmarking page done in collaboration with ARSC and hosted at ARSC.

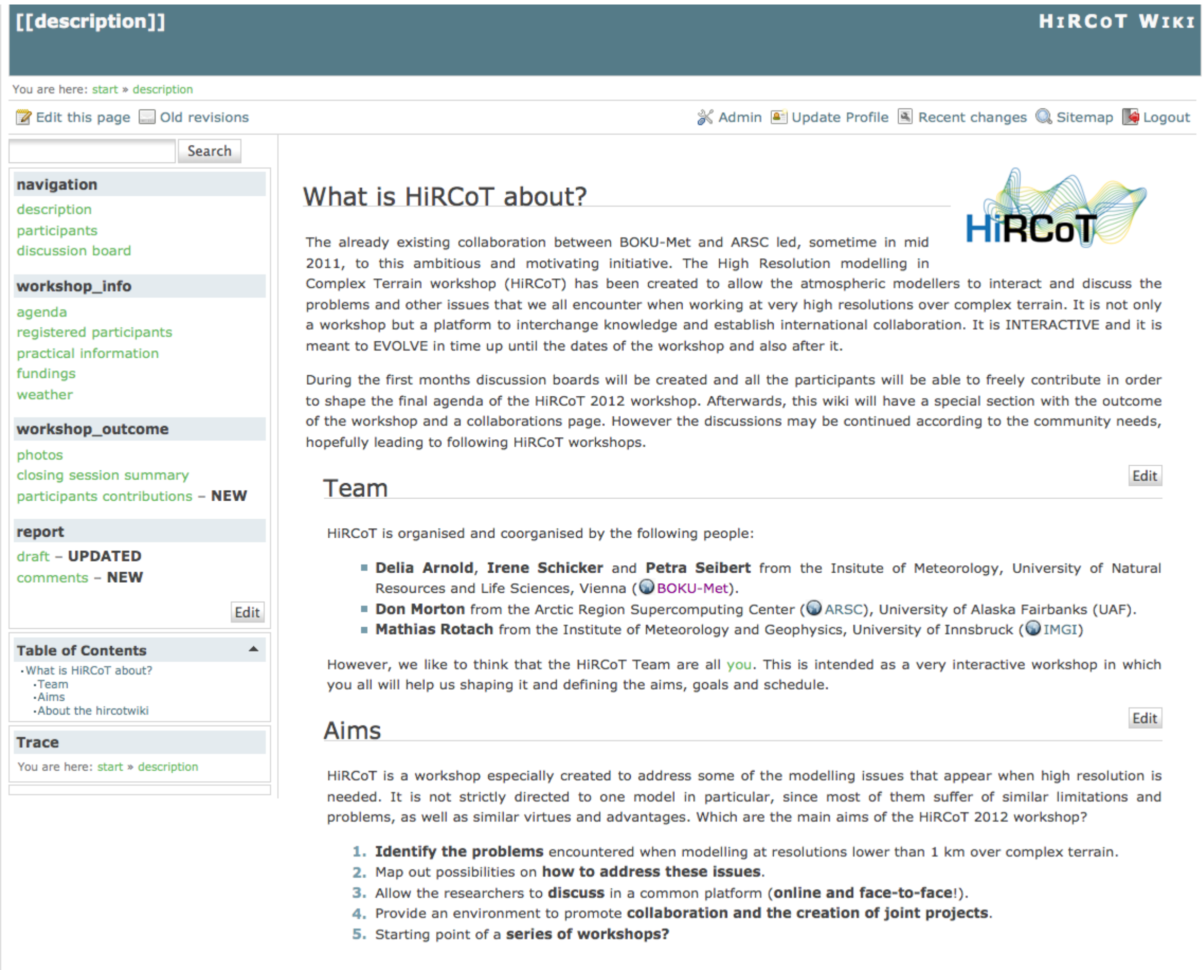


Figure 7.1: Snapshot of the HiRCoT wikipage.

8 Annex

8.1 Annex part 1: Description of the computer platforms used in HiRmod

1. **Vienna Scientific Cluster:** operated to satisfy the demand for High Performance Computing at the University of Vienna, the Vienna University of Technology, and the University of Natural Resources and Life Sciences.
   - Sun Fire X2270 compute nodes, each equipped with 2 Quadcore processors (Intel, X5550, 2.66 GHz) and 24 GB memory (3 GB per core).
   - Infiniband QDR network (40 Gbps).
   - Filesystem – ext2.

2. **Pacman**: academic system at the Arctic Region Supercomputing Center, funded by NSF in support of the Pacific Area Climate Monitoring and Analysis Network (P ACMAN). Penguin Computing Cluster with:

- Sixteen-core compute nodes consisting of 2 eight-core 2.3 GHz AMD Opteron processors with 64 GB memory (4 GB per core).
- Mellanox QDR Infiniband interconnect.
- Panasas version 12 file scratch file system.

3. **Kraken**: Cray XT5 at National Institute for Computational Sciences.
   - 12-core compute nodes consisting of 2 six-core 2.6 GHz AMD Opteron processors with 16 GB memory (1.5 GB per core).
   - Cray SeaStar2+ interconnect.
   - Lustre file system used on compute nodes.

4. **Chugach:** Cray XE6 currently administered by ARSC for the DoD High Performance Computing and Modernization Program.
   - 16-core compute nodes consisting of 2 eight-core 2.3 GHz AMD Opteron processors with 32 GB memory (2 GB per core).
   - CrayGemini interconnect.
   - Lustre file system used on compute nodes.

5. **imp3:** BOKU-MET Sun Fire X4150 server used for shared memory test of MM5 and WRF.
   - 2x Intel Xeon L5450 3.0 GHz Quad-Core processors with 32 GB RAM

6. **imp9:** BOKU-MET server used for shared memory test of MM5 and WRF.
   - Supermicro 2P-Dual-Core Opteron 2.4 GHz with 4 GB RAM

7. **Nona:** BOKU numbercruncher server used for shared memory test of MM5 and WRF.
   - 2xIntel E5520 2,26GHz (QuadCore) with 73 GB RAM

8.2 Annex part 3: Supplementary figures and tables

These figures and tables are referenced in the Section 2.2 of the report, but due to the page limit presented here.

8.2.1 WP 1 Computational aspects

Table 8.2.1.1: Comparison of run times for a 48~h benchmark run, expressed as wall-clock time per hour simulated. ***imp*** **refers to to machines available at BOKU-Met.**

Machine	Compiler	Wall-clock time (h)	# cores	Processor
VSC	ifort v11.1	3 h 30 min	8	Intel Xeon X5550 @ 2.66 GHz
imp3	ifort v10.0	4 h 38min	8	Intel Xeon Quad Core E5450 @ 3.00GHz
PHOENIX	ifort v9.1	5 h 05 min	16	Intel E5472 Quad Core @ 3.00GHz
VSC	gfortran v4.3.1	7 h 20 min	8	Intel Xeon X5550 @ 2.66 GHz
imp3	gfortran v4.3.1	9 h 30 min	8	Intel Xeon Quad Core E5450 3.00 GHz
imp9	ifort v9.1	12 h 00 min	4	Dual Core AMD Opteron 280 2.4 GHz

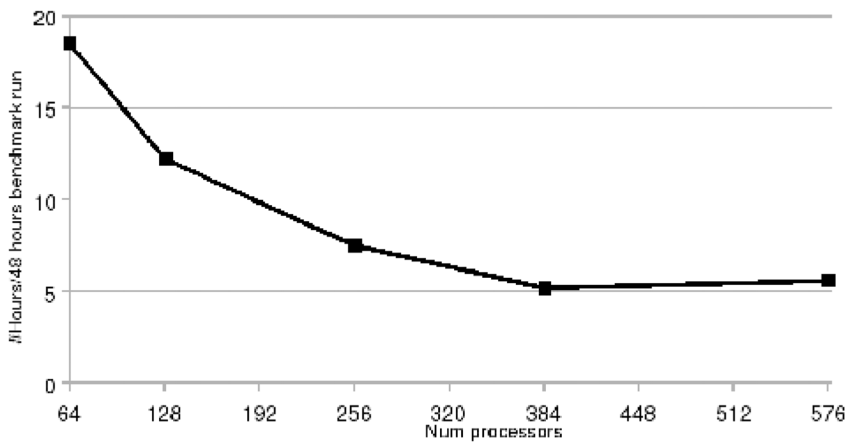


Figure 8.2.1.1: MM5 scalability: Wall-clock time in hours for a 2-day benchmark simulation as a function the number of cores

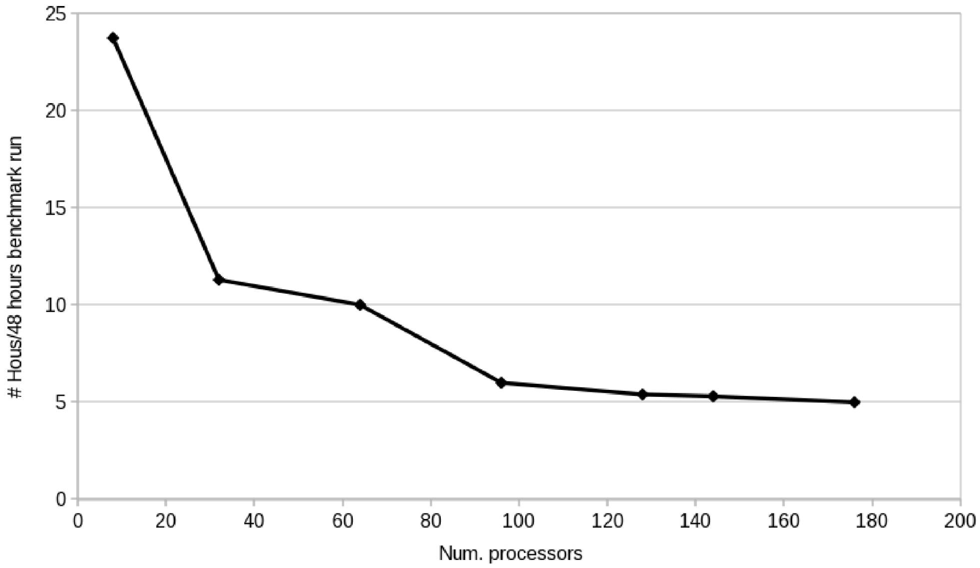


Figure 8.2.1.2: WRF scalability: Wall-clock time in hours for a 2-day benchmark simulation as a function the number of cores.

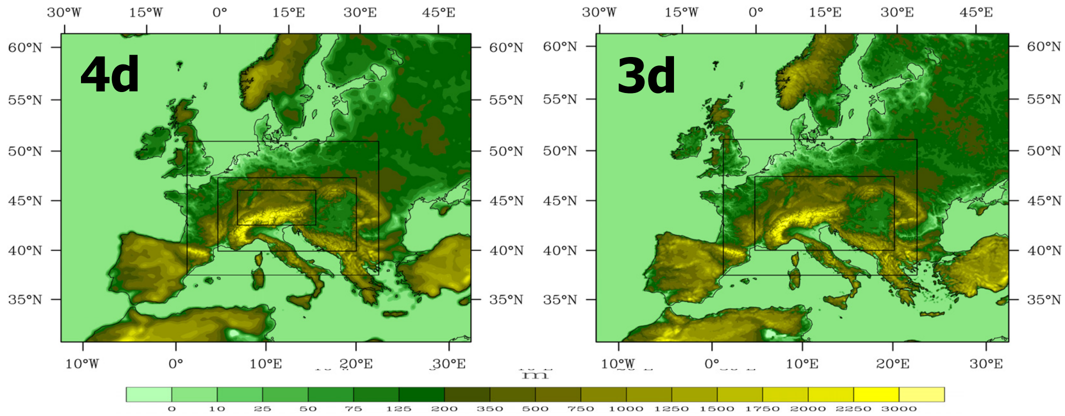


Figure 8.2.1.3: 4-domain and 3-domain configuration of the cases for the European Benchmark suite.

Table 8.2.1.2: 4-domain and 3-domain configuration of the European benchmarking suite

Domain	Grid points		Total number of cells ($\times 10^6$)		Horizontal resolution
	4 domains	3 domains	4 domains	3 domains	in km
1	96 x 167 x 40/63		0.7 / 1		21.6
2 / 1	274 x 217 x 40/63	585 x 459 x 63	2.4 / 3.7	16.9	7.2
3 / 2	592 x 355 x 40/63	823 x 652 x 63	8.4 / 13.2	33.8	2.4
4 / 3	1003 x 505 x 40/63	1777 x 1066 x 63	20.3 / 31.9	119.3	0.8

Metrics for model performance evaluation:

- **Wall-clock time –** this is the time required for a simulation to run, as measured in human terms, by using the difference between the time the simulation ends and the time the simulation started. This is typically the time of most interest to the user, because it describes how long a given simulation will take. However, other issues are of importance, too, particularly when users are constrained by costs of computer time, I/O, etc.
- **Speed-up –** is the fraction between the execution time of a run using a single processing element run and when using increasing number of parallel processing units. For the sizes of our problems, single processor runs were not possible due to memory limitations, therefore the speed-up is referenced to the run with the minimum number of processing units achieved.
- **Efficiency –** this is a value between 0 and 1, indicating the ratio of speedup to the number of PEs. This value typically indicates how well the PEs are utilised, with a value of 1 suggesting that we get a perfect speedup.
- **I/O time –** the wall-clock time required for the I/O operations alone.

- **Integration time** **-** we define *integration time* as the wall-clock time spent in calculations (model integration). This is the total wall-clock time minus the I/O time, and includes the communication between processing elements.

Benchmark results:

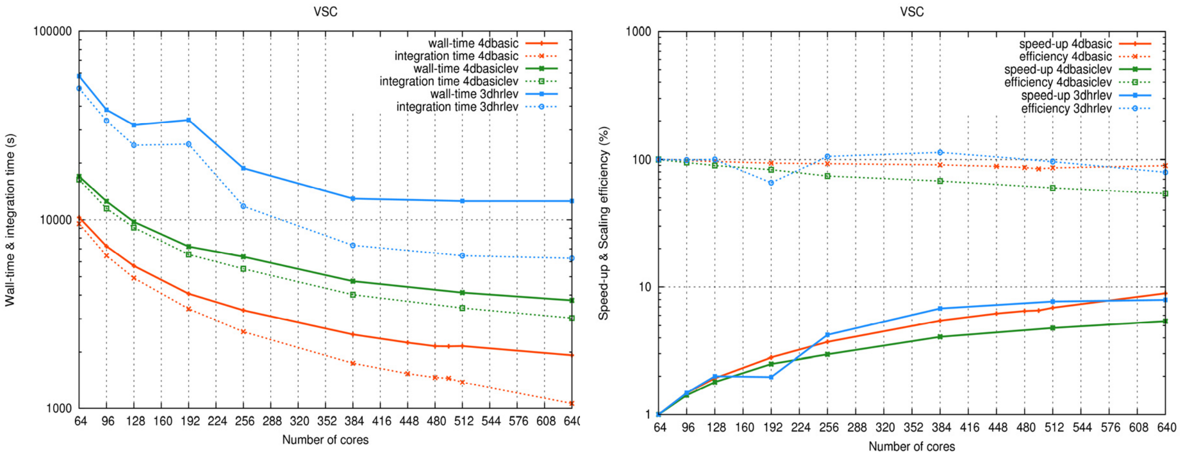


Figure 8.2.1.4 VSC total wall and integration (left panel) and speed-up and efficiency for increasing number of cores and the 4dbasic, 4dbasiclev and 3dhrlev cases.

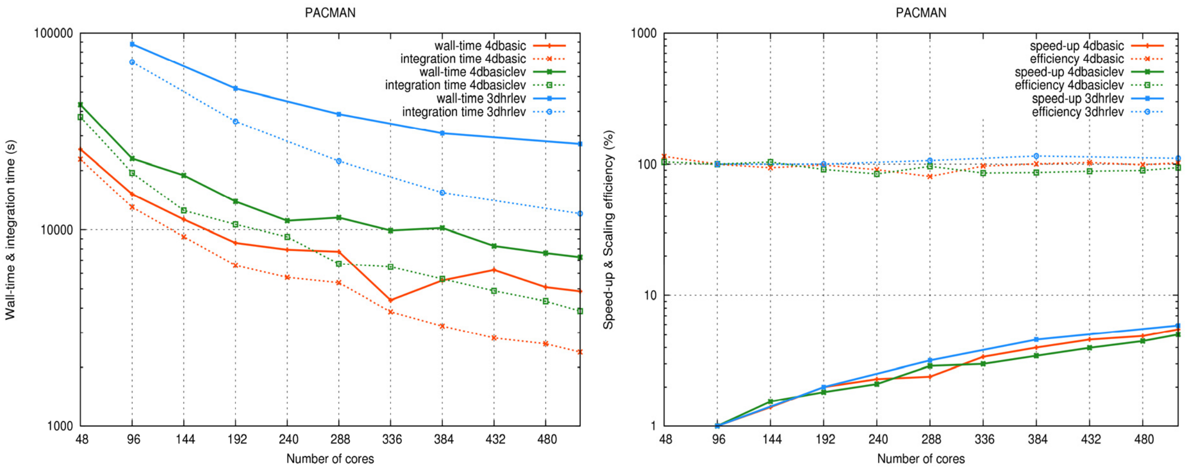


Figure 8.2.1.5: PACMAN total wall and integration (left panel) and speed-up and efficiency for increasing number of cores and the 4dbasic, 4dbasiclev and 3dhrlev cases.

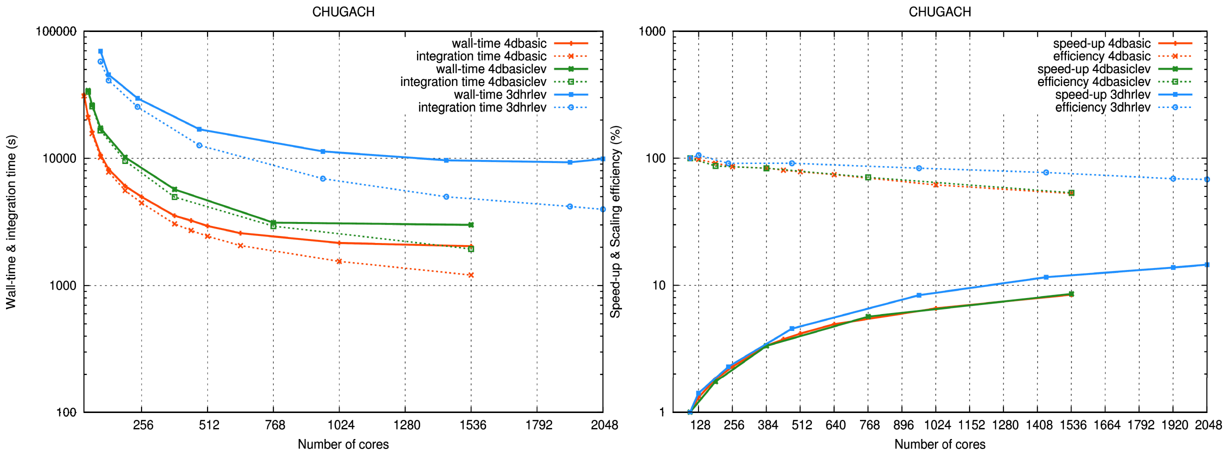


Figure 8.2.1.6: CHUGACH total wall and integration (left panel) and speed-up and efficiency for increasing number of cores and the 4dbasic, 4dbasiclev and 3dhrlev cases.

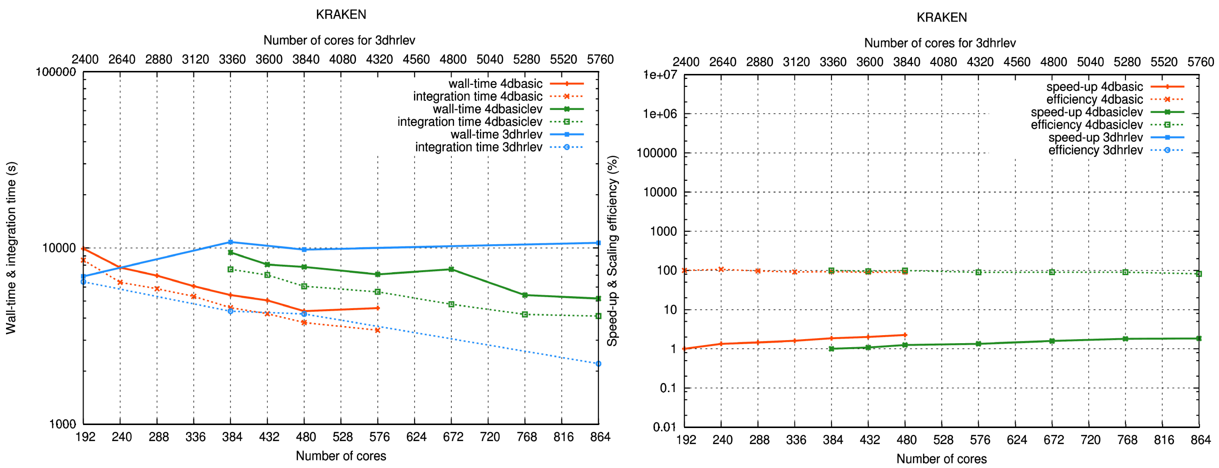


Figure 8.2.1.7: KRAKEN total wall and integration (left panel) and speed-up and efficiency for increasing number of cores and the 4dbasic, 4dbasiclev and 3dhrlev cases.

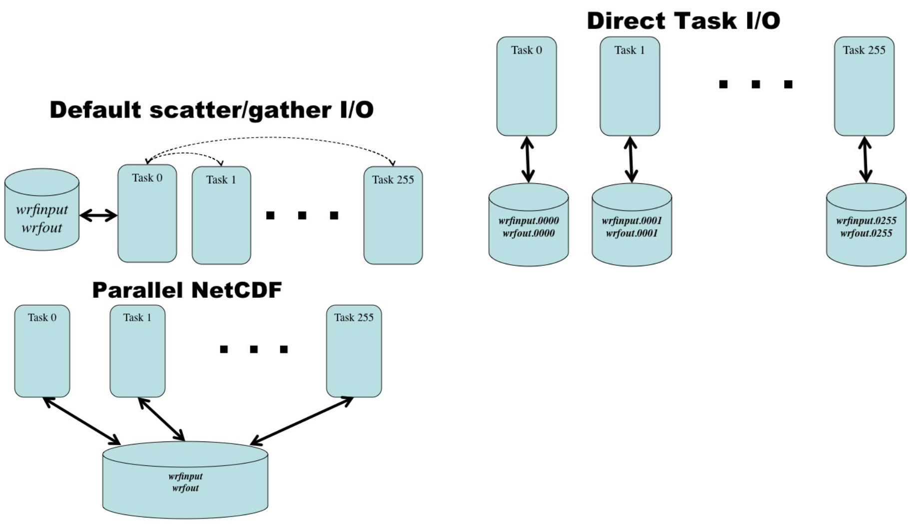


Figure 8.2.1.8: Diagrams of three of the different I/O options available in WRF. The quilting and netCDF diagram is not included due to the complexity of the drawing.

8.2.2 WP 2 Input and observational data

Table 8.2.2.1: Episodes selected for each of the regions.

Region	Episode	Remark
Black Forest	December 2004	strong inversion in winterly anticyclone
	June/July 2004	westerly flows with frontal passages
Vienna	July 2007	anticyclonic, hot summer period
	January 2007	one of the warmest January since begin of measurements
Inn Valley	January/February 2004	snow cover influence, moderate inversion
	July 2007	anticyclonic, hot summer period
All regions	Autumn 1999	Warm and dry September and October, cool November

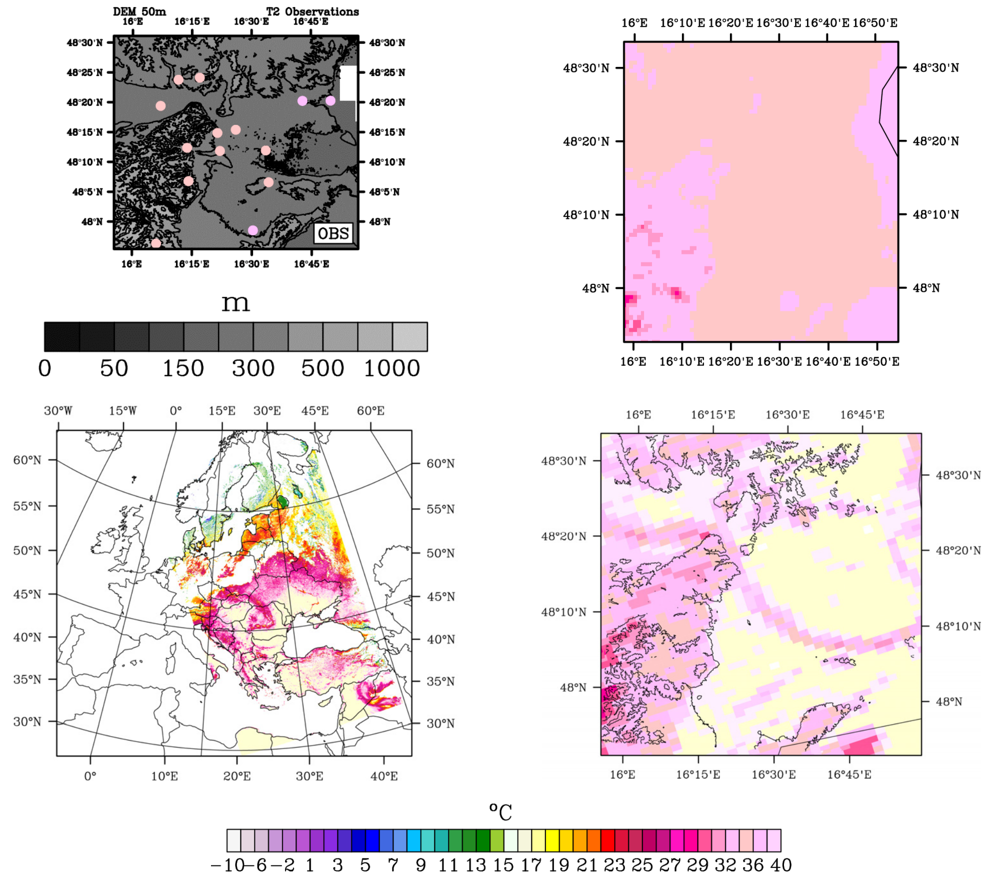


Figure 8.2.2.1: Comparison of 2 m station observations (top left), INCA 2 m temperature output (original WRF setup without modifications, top right), two merged MODIS LST tiles (bottom left), and the MODIS data (bottom right) for the Vienna region. Mind, satellite data represents the land surface temperature NOT the 2 m temperature. For comparing with model results one needs to used the corresponding parameter, TSK (surface skin temperature).

8.2.3 WP 3 Model improvements

Table 8.2.3.1: Comparison of GTOPO30 and SRTM 3″ elevation data for the Innsbruck region as in Figure 3.4.3.2. Parameters shown are the maximum and minimum elevations in the three innermost domains where the background elevation information is changed from GTOPO30 to SRTM 3″, the RMSE, correlation coefficient R, and the bias between the two different data sets. All values in m.

domain	Grid distance	SRTM 3″ (min / max)	GTOPO30 (min / max)	RMSE	R	BIAS
D3	2.4 km	31 / 3544	26 / 3619	105	0.99	7.0
D4	0.8 km	244 / 3534	222 / 3525	126	0.98	5.8
D5	0.27 km	448 / 3608	449 / 3505	157	0.97	3.6

Figure 8.2.3.1: Google satellite images of the observation sites Reutte (left) and Pitztal Gletscher (right). In the USGS land-use data Reutte is classified as “dryland, cropland and pasture” whereas in the remapped CLC06 data it is classified as “urban”. The Pitztal Gletscher station is classified as “glacier” in the USGS data whereas in the remapped CLC06 data it is classified as “barren or sparsely vegetated” which represents more reality. Thus, simply remapping or using the newer land-use data works for some areas but not for all.

Table 8.2.3.2: Description of the 24 USGS / CLC06 classes and the 20 MODIS classes.

Class	USGS / CLC06	MODIS
1	Urban and Built-Up Land	Evergreen Needleleaf Forest
2	Dryland Cropland and Pasture	Evergreen Broadleaf Forest
3	Irrigated Cropland and Pasture	Deciduous Needleleaf Forest
4	Mixed Dryland/Irrigated Cropland/Pasture	Deciduous Broadleaf Forest
5	Cropland/Grassland Mosaic	Mixed Forests
6	Cropland/Woodland Mosaic	Closed Shrublands
7	Grassland	Open Shrublands
8	Shrubland	Woody Savannas
9	Mixed Shrubland/Grassland	Savannas
10	Savanna	Grasslands
11	Deciduous Broadleaf Forest	Permanent wetlands
12	Deciduous Needleleaf Forest	Croplands
13	Evergreen Broadleaf Forest	Urban and Built-Up
14	Evergreen Needleleaf Forest	cropland/natural vegetation mosaic
15	Mixed Forest	Snow and Ice
16	Water Bodies	Barren or Sparsely Vegetated
17	Herbaceous Wetland	Water
18	Wooded Wetland	Wooded Tundra
19	Barren or Sparsely Vegetated	Mixed Tundra
20	Herbaceous Tundra	Barren Tundra
21	Wooded Tundra	
22	Mixed Tundra	
23	Bare Ground Tundra	
24	Snow or Ice	

8.2.3.1 Description of ECMWF input data study episode

On August 14, a cut-off low with a strong jet moved from the Northwest towards the Alps, crossing on August 15 precipitating in nearly all regions of Austria moving to the northern Adriatic Sea and continuing in the following days slowly towards the Southeast. From the Southeast, moist and warm air warm air was transported around the eastern Alps precipitating on the northern side of the Alps and causing floodings in the eastern part of Austria. The amount of precipitation during this event reached between 75 – 100% of the climatological mean in Switzerland and the western Austria. This saturated the soils before the second precipitation event which caused the major floodings 2005 in Austria, especially in the Inn Valley. Figure 8.2.3.2 shows the different kinds of input data used and results from comparison with data from the Innsbruck Airport observation site.

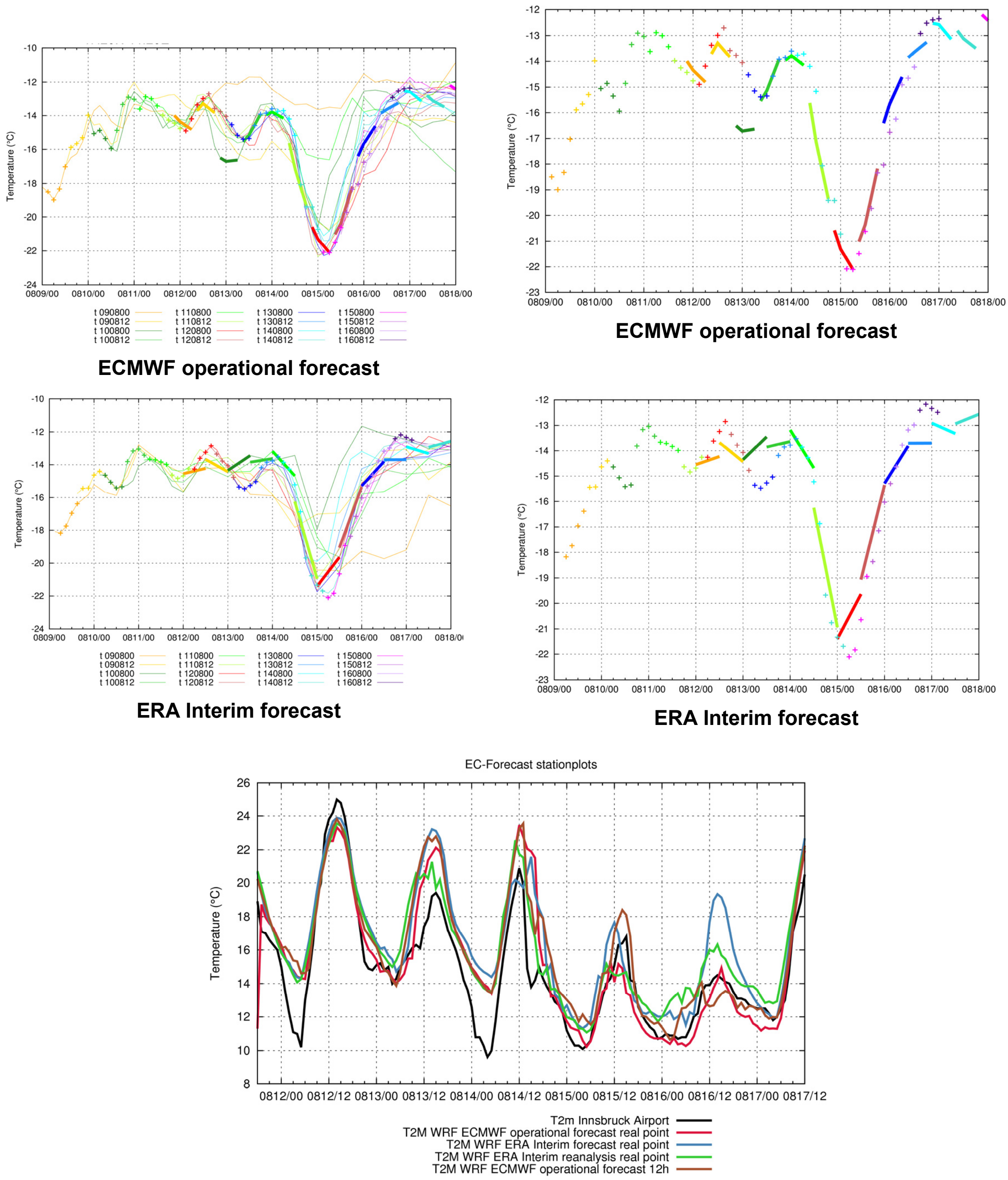


Figure 8.2.3.2: Input data for the initialisation of WRF using ECMWF operational forecast (top) and ERA Interim forecast (middle). The thin lines in the spaghetti plots (left column) denote the forecast hours of each forecast run, the thick highlighted ones are the data used for initialisation of each of the forecast run. Crosses denote what hours of the forecast runs can be used as "verifying analysis". In the right column only the forecast hours used as initialisation are plotted. The bottom plot shows a comparison of the simulated 2 m temperature and the observations at the Innsbruck Airport station. The ERA Interim data are shown in blue (forecast) and green (reanalysis), in red the operational forecast (6h input) and brown (12 h input).

Table 8.2.3.3: RMSE, BCRMSE, R, and BIAS of the different initialised WRF simulations for the Innsbruck Airport station.

	OpFC	Op12	EIFC	EIRE
RMSE	1.93	1.99	2.25	1.85
BCRMSE	1.81	1.56	1.65	1.29
R	0.88	0.89	0.88	0.93
BIAS	0.65	1.24	1.68	1.32

8.2.4 WP 4: Assessment and comparison

Table 8.2.4.1: Important namelist parameters used in this study. The grid nudging option is applied for case studies only, not for the time slice simulation as grid nudging is not an option in climate simulations.

Parameter	Option used
Model top	50 hPa
Model levels	39/60
Microphysics	Lin et al.
Radiation	RRTM / CAM longwave and Dudhia shortwave
Land surface	Noah LSM
Boundary layer	MYNN 2.5 TKE scheme
Cumulus	Betts-Miller-Janjic cumulus in outermost domain

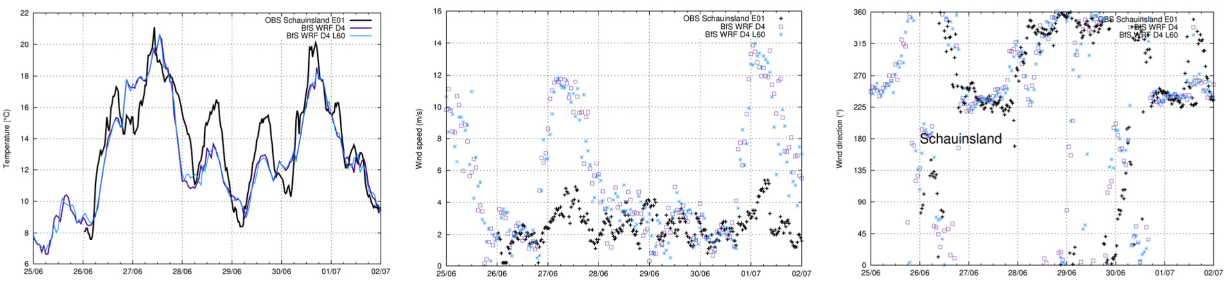
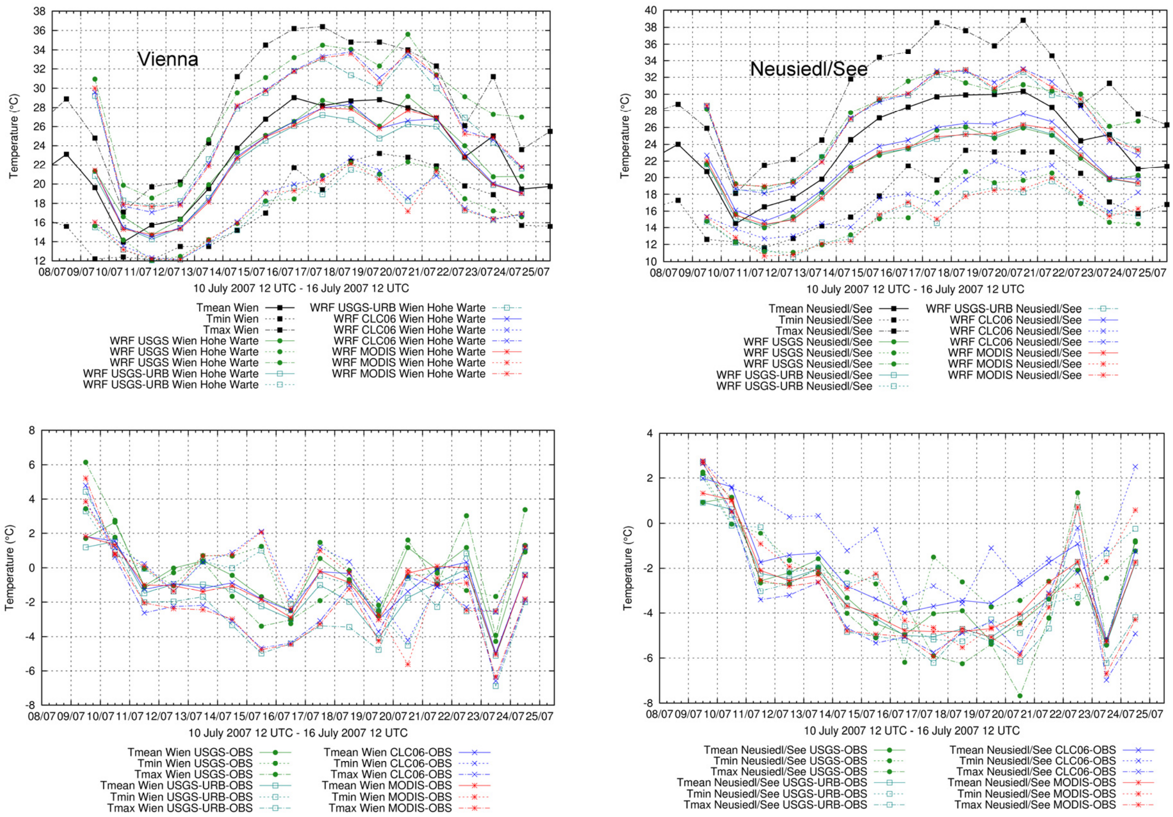


Figure 8.2.4.1: Comparison of WRF Schauinsland simulation for the observation site Schauinsland using 40 (purple) and 60 levels (blue) vertical levels using the temperature, wind speed, and wind direction of the lowest model level. A difference between the two simulations is hardly visible, also for the other observation sites of this ROI (not shown here).

Table 8.2.4.2: Simulations carried out for the land-use comparison.

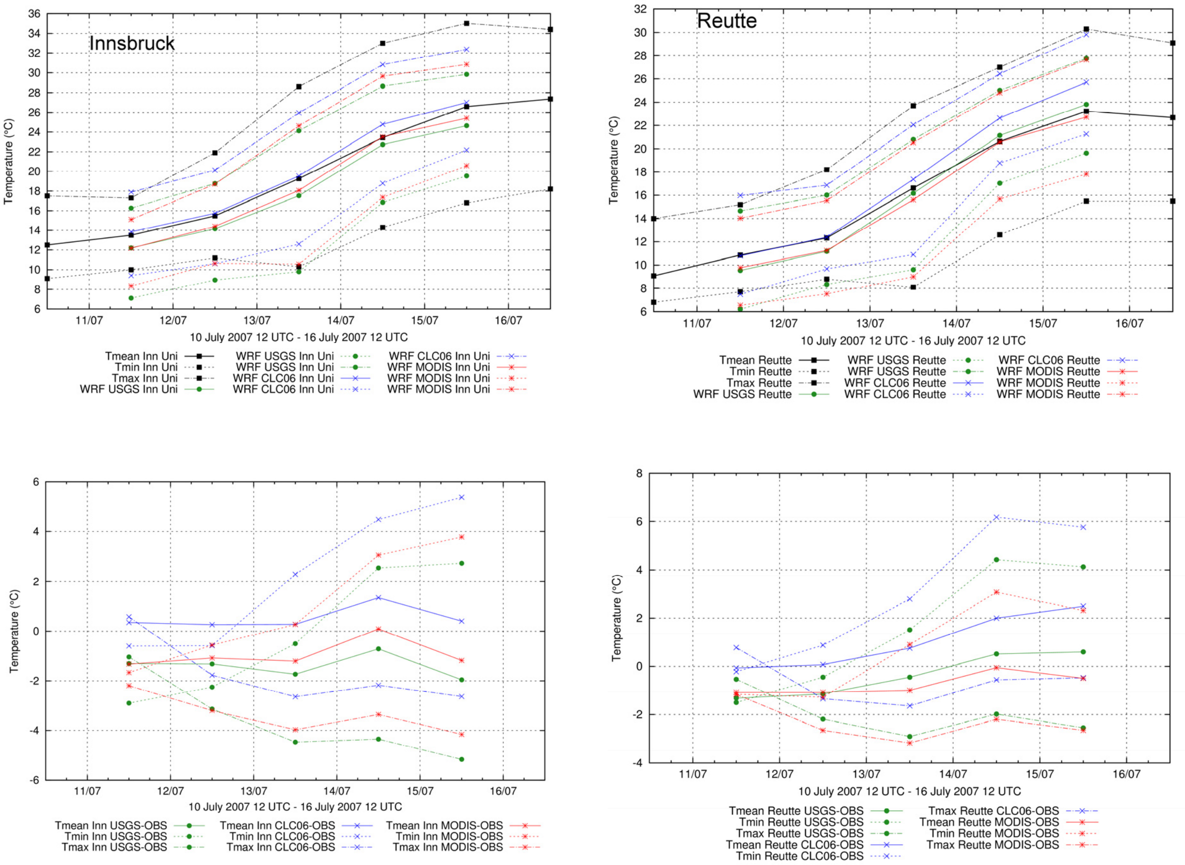
ROI	USGS	USGS-URB	CLC00	CLC06	MODIS	# Domains / Resolution
Vienna basin	√	√		√	√	5 / 0.8 km
Inn Valley	√		√	√	√	4 / 0.8 km



	T				FF			
	USGS	USGS-U	CLC2U	MODIS	USGS	USGS-U	CLC2U	MODIS
XMEAN	295.26	294.80	295.21	295.30	3.98	2.79	2.56	2.67
YMEAN	296.34	296.34	296.34	296.34	3.63	3.63	3.63	3.63
BIAS	−1.08	−1.54	−1.13	−1.05	0.35	−0.85	−1.08	−0.96
RB	−0.17	−0.25	−0.18	−0.17	0.17	−0.41	−0.52	−0.47
XVAR	29.77	28.98	31.15	28.85	7.30	2.95	2.34	2.54
YVAR	39.74	39.74	39.74	39.74	4.25	4.25	4.25	4.25
XSTD	5.46	5.38	5.58	5.37	2.70	1.72	1.53	1.59
YSTD	6.30	6.30	6.30	6.30	2.06	2.06	2.06	2.06
R	0.90	0.90	0.90	0.91	0.40	0.44	0.42	0.46
RMSE	2.93	3.13	3.02	2.85	2.69	2.19	2.27	2.17
BCRMSE	2.93	3.13	3.02	2.85	2.69	2.19	2.27	2.17
SB	0.77	0.62	0.76	0.78	0.78	0.37	0.27	0.31
SR	0.90	0.90	0.90	0.91	0.40	0.44	0.42	0.46
STOT	0.85	0.78	0.85	0.86	0.72	0.53	0.46	0.50
RMSE (DD)					68.38	57.23	62.71	60.55
SDD					0.38	0.52	0.45	0.47

	T				FF			
	USGS	USGS-U	CLC2U	MODIS	USGS	USGS-U	CLC2U	MODIS
XMEAN	294.69	294.37	295.05	291.40	4.33	4.54	4.05	4.14
YMEAN	297.35	297.35	297.35	296.20	2.80	2.80	2.80	2.71
BIAS	−2.66	−2.97	−2.30	−4.80	1.53	1.74	1.25	1.43
RB	−0.41	−0.45	−0.35	−0.69	1.09	1.24	0.89	1.02
XVAR	25.49	26.11	27.21	371.86	4.64	5.77	4.29	4.35
YVAR	43.04	43.04	43.04	47.94	1.98	1.98	1.98	1.99
XSTD	5.05	5.11	5.22	19.28	2.15	2.40	2.07	2.08
YSTD	6.56	6.56	6.56	6.92	1.41	1.41	1.41	1.41
R	0.92	0.93	0.93	0.26	0.20	0.46	0.48	0.56
RMSE	3.82	3.94	3.48	19.35	2.79	2.77	2.24	2.25
BCRMSE	3.82	3.94	3.48	19.35	2.79	2.77	2.24	2.25
SB	0.38	0.33	0.45	0.17	$7.82\ 10^{-02}$	$6.11\ 10^{-02}$	0.11	$8.82\ 10^{-02}$
SR	0.92	0.93	0.93	0.26	0.20	0.46	0.48	0.56
STOT	0.64	0.62	0.68	0.21	0.29	0.31	0.38	0.38
RMSE (DD)					75.67	64.10	65.28	
SDD					0.32	0.43	0.42	

Figure 8.2.4.2: Tmin, Tmax, and Tmean (upper row) and their errors compared to the observations (middle row) for two selected stations of the Vienna basin land-use simulations. Observation data are shown black, WRF USGS in green, WRF USGS-URBAN in seagreen, WRF CLC06 in blue, and MODIS data in red. Vienna represents here (left column) the observation site Wien Hohe Warte, which is close to the centre of the domain. Neusiedl/See (right column) is located close to the model domain and also represents a different climate compared to Wien Hohe Warte. Especially for the site Wien Hohe Warte the difference between USGS-URB and the CLC06 and MODIS data shows an improvement when using the updated land-use data sets. Comparison between USGS and USGS-URBAN shows that for this site the USGS simulations performs better. For the Neusiedl/See site the results of the CLC06 simulation perform best. The bottom row shows some statistics as BIAS, R, RMSE for both sites.



	T				FF			
	USGS	CLC00	CLC06	MODIS	USGS	CLC00	CLC06	MODIS
XMEAN	291.8668	292.4674	292.5375	291.2597	2.860773	3.186398	3.172260	3.692198
YMEAN	292.8447	292.8447	292.8447	292.8447	6.188889	6.188889	6.188889	6.188889
BIAS	-0.9779053	-0.3773499	-0.3071899	-1.585022	-3.328116	-3.002491	-3.016629	-2.496691
RB	-0.1382415	-5.3344049E-02	-4.3425895E-02	-0.2240666	-1.368600	-1.234696	-1.240510	-1.026699
XVAR	39.46579	39.23835	39.30056	38.10364	5.839366	6.969625	7.211214	10.21303
YVAR	50.03990	50.03990	50.03990	50.03990	5.913487	5.913487	5.913487	5.913487
XSTD	6.282181	6.264052	6.269016	6.172814	2.416478	2.640005	2.685370	3.195783
YSTD	7.073889	7.073889	7.073889	7.073889	2.431766	2.431766	2.431766	2.431766
R	0.9361609	0.9338158	0.9348660	0.9361351	-0.5677281	-0.6017528	-0.6061218	-0.6388556
RMSE	2.694010	2.581440	2.553301	2.983558	5.431529	5.442832	5.490077	5.682392
BCRMSE	2.694010	2.581440	2.553301	2.983558	5.431529	5.442832	5.490077	5.682392
SB	0.8395550	0.9723315	0.9814910	0.6657531	5.0682522E-02	6.1558396E-02	6.1017871E-02	8.6646855E-02
SR	0.9361609	0.9338158	0.9348660	0.9361351	-0.5677281	-0.6017528	-0.6061218	-0.6388556
STOT	0.8970621	0.9625430	0.9674724	0.8080341	0.1334050	0.1296719	0.1280158	0.1271918

	T				FF			
	USGS	CLC00	CLC06	MODIS	USGS	CLC00	CLC06	MODIS
XMEAN	289.8208	290.0172	290.2587	289.5474	2.691141	2.419417	2.578502	2.850383
YMEAN	289.7933	289.7933	289.7933	289.7933	6.985417	6.985417	6.985417	6.985417
BIAS	2.7465820E-02	0.2238159	0.4653931	-0.2459717	-4.294275	-4.566000	-4.406915	-4.135034
RB	4.2456994E-03	3.4597732E-02	7.1941011E-02	-3.8022596E-02	-2.529818	-2.689895	-2.596175	-2.436007
XVAR	41.76233	41.87391	42.43329	38.24660	2.007936	1.884872	2.407949	1.585643
YVAR	41.84916	41.84916	41.84916	41.84916	2.881384	2.881384	2.881384	2.881384
XSTD	6.462378	6.471005	6.514084	6.184383	1.417017	1.372906	1.551757	1.259223
YSTD	6.469092	6.469092	6.469092	6.469092	1.697464	1.697464	1.697464	1.697464
R	0.8995979	0.8988594	0.9017691	0.9310181	-0.2443042	-0.3895639	-0.3850580	-0.2159176
RMSE	2.897474	2.918575	2.915029	2.379122	4.950292	5.237398	5.170953	4.742211
BCRMSE	2.897474	2.918575	2.915029	2.379122	4.950292	5.237398	5.170953	4.742211
SB	0.9998198	0.9881715	0.9507917	0.9857488	1.5384666E-02	1.3632271E-02	1.4619612E-02	1.6572403E-02
SR	0.8995979	0.8988594	0.9017691	0.9310181	-0.2443042	-0.3895639	-0.3850580	-0.2159176
STOT	0.9748088	0.9688006	0.9508154	0.9746523	0.1905870	0.1527542	0.1598137	0.1878138

Figure 8.2.4.3 Tmin, Tmax, and Tmean (upper row) and their errors compared to the observations (middle row) for two selected stations of the Inn Valley land-use simulations. Observation data are shown black, WRF USGS in green, WRF CLC06 in blue, and MODIS data in red. Innsbruck represents here (left column) the observation site Innsbruck University, which is close to the centre of the domain. Reutte (right column) is located in the western half of the model domain. Tmean of the CLC06 simulation for the site Innsbruck shows good results compared to the observations and the other runs. Also Tmax of the CLC06 run is in good agreement. But, as mentioned in the main text, Tmin is overestimated, also by the other two simulations. The bottom row shows some statistics as BIAS, R, RMSE for both sites with results of a simulation using also the CLC00 data.

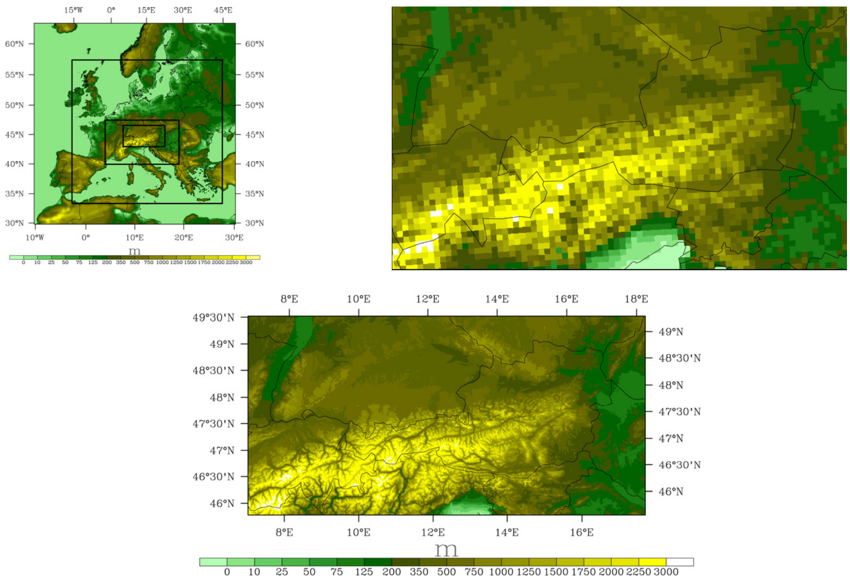


Figure 8.2.4.4: Domain layout of the long run (top left) and comparison of the representation of Austrian in the reclip:century 10 km MM5 domain (zoom, top right) and the innermost domain of the long run with 0.8 km resolution.

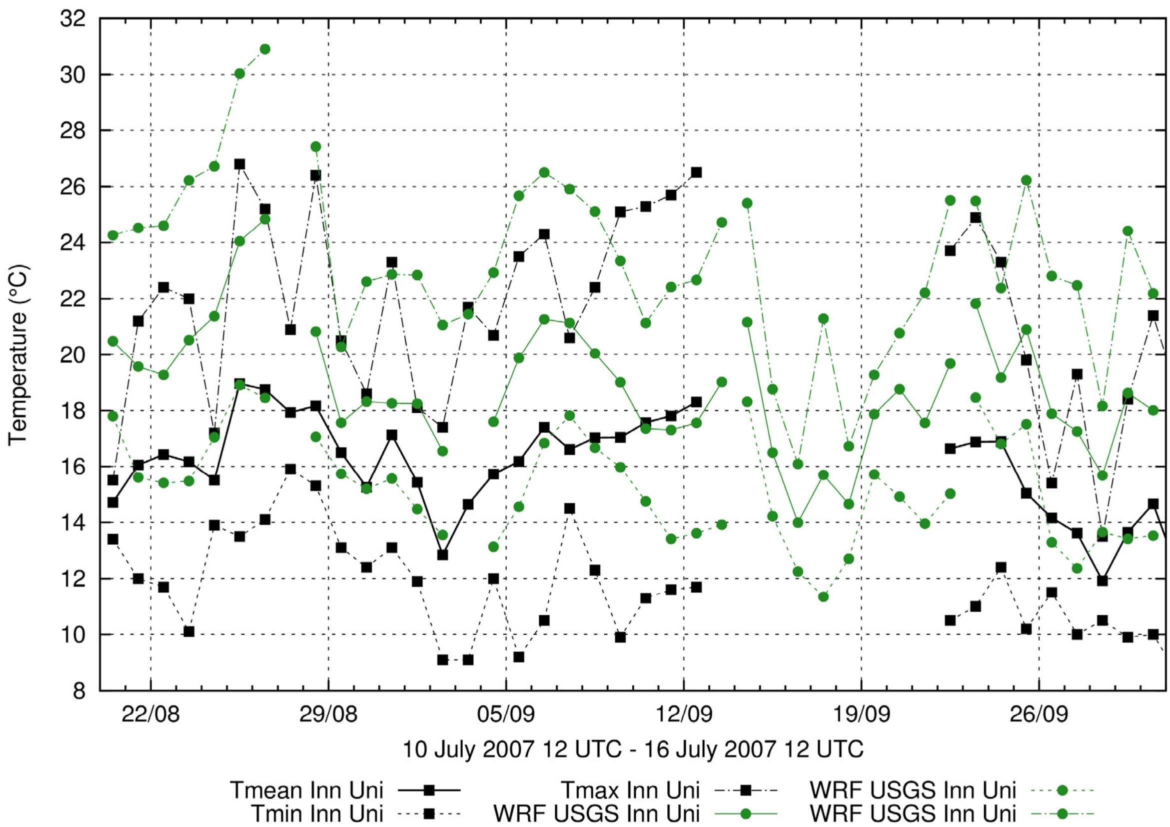


Figure 8.2.4.5: Tmin, Tmax, and Tmean simulated (in green) in the available part of the long run compared to observations at the station Innsbruck University (in black).

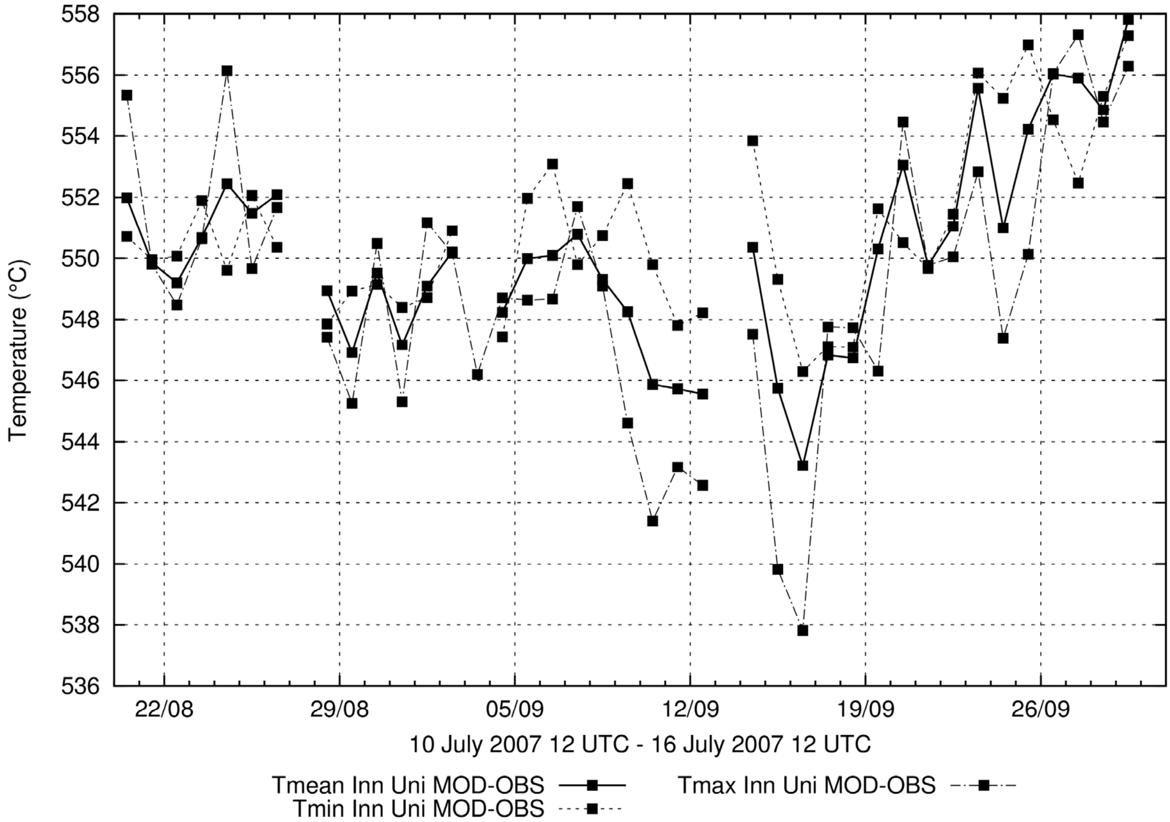


Figure 8.2.4.6: Deviation of Tmin, Tmax, and Tmean from observations (obs–model) at the station Innsbruck University for the available part of the long run.