SCALMET – a tool for coupling regional climate models with physically-based simulations of land surface processes

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Abstract

The coupling tool SCALMET was developed to bridge the scales between regional climate models and the land surface model components within the DANUBIA model system. Since terrestrial model components require high-resolution atmospheric forcings, different scaling techniques ranging from direct interpolation methods to quasi-physically based and statistical approaches have been applied to adequately remap regional climate model outputs. SCALMET scales up land surface model outputs and provides aggregated surface fluxes as input for the meteorological model. Thereby it provides the technical prerequisite to model climate response on changing conditions at the earth's land surface.

Keywords: coupled model systems, downscaling, global change, GLOWA-Danube, hydrological modelling, IPCC

1 Introduction

To understand and to predict the potential effects of climate change on water resources, it is necessary to consider (i) the nonlinearity and complexity of the interactions between the atmosphere and the land surface and (ii) the mutual dependency of the respective processes at the investigated scale.

A variety of regional climate models (RCMs) have recently been used to provide climate change scenarios at regional scales. The resulting climate simulations provide the required meteorological input for large-scale hydrological models. However, the gap of the scales to be bridged still represents a scientific challenge. In Alpine areas, the topographic gradient embodies the most significant uncertainty in the downscaling result. Due to coarse spatial model resolutions, RCM outputs do not fully capture environmental variability in mountainous regions with steep climate gradients. Modelling the atmosphere at low spatial resolutions implies a coarser representation of topography. Figure 1 shows the terrain elevation for the model domain of the Upper Danube Watershed in different spatial resolutions. As displayed, the Alps are increasingly 'flattened' with decreasing spatial resolution. The result is a local height discrepancy between the orography of the simulation and the real orography and in consequence, a discrepancy between simulated and observed meteorological variables. An appropriate downscaling technique can reduce this gap (Früh et al. 2006).

As part of the global change decision support system DANUBIA (Mauser & Ludwig 2002), the coupling tool SCALMET has been developed to preprocess me-

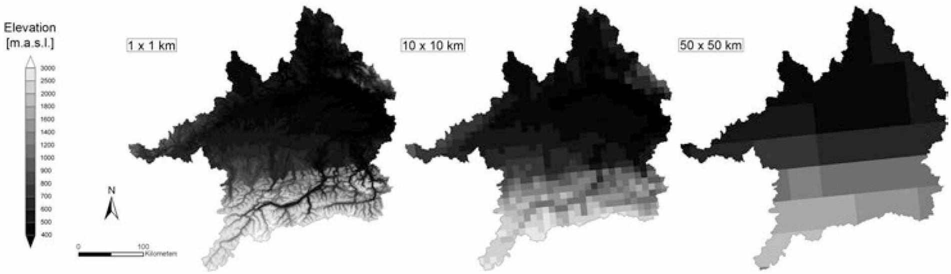

Figure 1: The representation of orography in the Upper Danube River Chatchment at different spatial resolutions.

teorological model outputs for hydrological and socio-economic modelling in the Upper Danube River Catchment. Different scaling techniques ranging from direct interpolation methods to quasi-physically based and statistical approaches have been implemented in SCALMET to adequately remap RCM output. Compared to direct interpolators, these techniques partly compensate the loss of climatic variability due to the coarse spatial resolution in regional climate models. Since high-resolution modelling of surface fluxes vice-versa contributes to improvements in meteorological models, SCALMET scales up land surface model outputs and provides aggregated surface fluxes as input for the meteorological model. For these two-way coupled model runs conservative interpolation methods have been implemented into the software interface to treat fluxes in a conservative manner within the remapping process. In the framework of the GLOWA-Danube project, SCALMET is used for both, the downscaling of meteorological model outputs in one-way coupled model runs (REMO, MM5 and CLM) and for the upscaling of land surface model calculations in two way coupled model setups (REMO and MM5). The latter offers the technical prerequisite to model climate response to changing conditions at the earth's land surface. Figure 2 gives an overview over the coupled model system and the variables exchanged between the model components.

2 Models

2.1 Simulation of atmospheric processes

Within the GLOWA-Danube project, different meteorological models simulate the atmosphere, as for instance the 5th generation Penn State University and National Center of Atmospheric Research model MM5 (Grell et al. 1994). The model provides hourly meteorological data in a spatial resolution of 45 x 45 km. Since the beginning of the 3rd project phase, data from the regional climate model REMO (Jacob 2001) is applied as well. With grid boxes covering 10 x 10 km at the earth's surface, the model exceeds the spatial resolution of most other climate models. REMO also provides atmospheric fields on an hourly basis. The CLM model is the third model simulating the atmosphere (Böhm et al. 2006). In the current configuration, the model provides data in a spatial resolution of 50 x 50 km with a tempo-

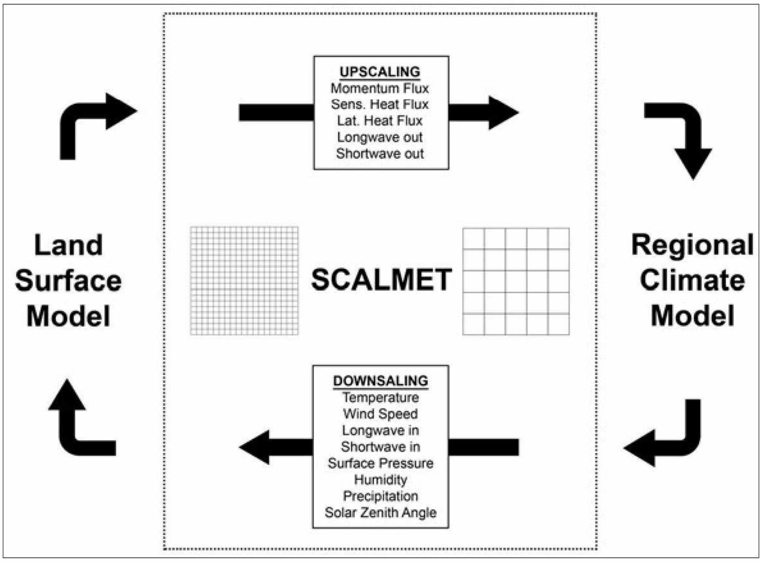

Figure 2: The coupled model system and the exchanged meteorological variables.

ral resolution of 3 hours. All these models are capable of delivering data for past and future climate conditions depending on the data used to force the model at the boundaries of the model domain.

2.2 Simulation of land surface processes

In the GLOWA-Danube Project, meteorological model output serves as input for the hydrological model component but also constitutes the driving force for many processes described in transdisciplinary model components (e.g. farming, tourism or traffic) (Mauser & Ludwig 2002). In a first approach, the RCMs are coupled only with the land surface component of the DANUBIA model system. In its current version the land surface component is a distributed, physical, non-calibrated regional Earth System model, which simulates all relevant water fluxes as well as vegetation processes on a 1 km grid base. By initially excluding socio-economic model components like farming, tourism or traffic, we maximise performance and maintain the potential to evaluate the quality of the meteorological inputs by means of water balance analysis.

3 Methods

The land surface component needs high-resolution distributions of air temperature, incoming longwave and shortwave radiation, wind speed, precipitation, surface pressure, and air humidity. These meteorological data can be obtained by the processing of regional climate simulations using different approaches.

3.1 Direct interpolation methods

The coupling tool SCALMET includes a roundup of direct interpolation algorithms like inverse distance or bilinear interpolation methods. Beyond these techniques, a conservative remapping method is implemented. This method guarantees conservation of mass, energy and momentum when meteorological fields are directly interpolated between different model scales (Jones 1998). Since direct interpolation methods do not compensate the loss of climatic variability caused by coarse climate model topography, these algorithms only produce satisfying results in combination with high-resolution climate model data or in flat terrain. Consequently, statistical and quasi-physically based approaches need to be implemented to adjust the different meteorological variables beyond the possibilities of direct interpolation methods. Still, direct interpolation algorithms constitute essential parts in the remapping processes described below.

3.2 Statistical downscaling methods

To downscale MM5 mesoscale atmospheric simulations, a statistical approach has been developed within the GLOWA-Danube project. The method estimates local subscale variability based on a high resolution observed climatology and accounts for the elevation dependence of each considered parameter. The results of this approach are monthly factors for temperature, humidity and wind speed, and daily factors for precipitation that can correct coarse resolution MM5 simulations (Früh et al. 2006). As the application of these factors is limited to the climate model MM5, alternative remapping methods were implemented to allow the application of the developed methods to the data of other regional climate models.

Many meteorological variables strongly depend on elevation, which can be observed in case of meteorological simulations as well (e.g. temperature, dewpoint temperature, precipitation, windspeed, longwave radiation and surface pressure). The dependence of a climate model simulation (X_{sim}) on climate model elevation (Z) forms the basis for a statistical analysis that can be performed for every model timestep. Once the function describing this elevation dependence best is determined, the elevation information (Z) in the spatial resolution of the climate model can be used to calculate a value (X_{cal}) for the considered meteorological variable for every grid box in the spatial resolution of the climate model:

$$X_{cal} = f(Z) \tag{1}$$

The same function can be used to calculate a value (x_{cal}) for the considered meteorological variable for every subgrid-cell using subgrid-elevation (z):

$$x_{cal} = f(z) \tag{2}$$

As the derived function will not reproduce the exact value, which the climate model simulated for each grid box, the algorithm produces a residuum (R) for every climate model grid box expressed as:

$$R = X_{sim} - X_{cal} \tag{3}$$

To account for these local differences between the meteorological simulations (X_{sim}) and the calculated values (X_{cal}), the residues (R) are interpolated to the subgrid-scale. The interpolated residues (r) can be used to correct the calculated subgrid-values (x_{cal}). A subgrid-value (x) can be computed as:

$$x = x_{cal} + r \tag{4}$$

Even though the interpolated residues (r) corrected the calculated subgrid-values (x_{cal}), the conservation of mass and energy between the climate model grid and the underlying land surface grid is not given in most cases. The simulated climate model value (X_{sim}) provides the amount of mass/energy to be distributed over the subgrid-cells. To calculate the mass/energy overrun or deficit, the mean value (X_{mean}) is computed considering all underlying subgrid-values (x_n)

$$X_{mean} = \frac{\sum_{n=1}^{N} (x_n \cdot a_n)}{\sum_{n=1}^{N} a_n} \tag{5}$$

where a_n is the area fraction of the considered climate model cell covered by the subgrid-cell (n) and N is the number of overlapping subgrid-cells. The difference (X_{diff}) between the mean subgrid-value (X_{mean}) and the climate model value (X_{sim}) requires interpolation to the subgrid-resolution. Finally, all subgrid-values (x) can be corrected with the interpolated difference (x_{diff}).

Total mass and energy conservation is only assured when (i) a conservative direct interpolation method is applied to interpolate the differences and, (ii) when the subgrid-values do not need to be corrected, to satisfy a special range of realistic values (precipitation must not be less than 0) subsequent to this conservative interpolation. However conservation is given to a large extend even when non-conservative direct interpolation methods are applied to interpolate the differences (X_{diff}).

3.3 Quasi-physically based downscaling methods

The following remapping methods could most adequately be described as quasi-physically based methods as physically based approaches are combined with statistical methods. All of these methods imply a local climate dependence on available subgrid-scale information (e.g. temperature-elevation relationships). Most of the presented methods have been used in other models to generate high resolution atmospheric forcings over complex terrain and have been validated for the application on both, observed and modelled meteorological variables (Liston & Elder 2006). To provide high resolution temperature distributions, the temperature simulations are adjusted to sea level using monthly temperature lapse rates and the climate model elevation. In a next step the reference level temperatures are directly interpolated and adjusted to the real subgrid-elevation

$$T = T_0 - (\tau \cdot z) \tag{6}$$

where T is the temperature at subgrid-elevation z, T_0 is the reference level temperature and τ is the temperature lapse rate.

As the implemented precipitation adjustment function is a nonlinear function of elevation difference, the interpolated climate model elevation is used as a reference level for precipitation-elevation adjustments instead of the sea level. Following Thornton (1997), the precipitation adjustment function can be written as

$$P(z) = P_0 \cdot \frac{(1 + \nu(z - z_0))}{(1 - \nu(z - z_0))} \tag{7}$$

where P_0 is the interpolated climate model precipitation, z_0 is the interpolated climate model elevation, z is the real subgrid-elevation and ν is the precipitation adjustment factor. Temperature lapse rates and precipitation adjustment factors are expected to vary widely over space and time. To optimise remapping results inside the Upper Danube watershed, both have been adjusted using data from the WorldClim database (www.worldclim.org) providing aggregated temperature and precipitation data for the period from 1950–2000 in form of monthly average values.

Since relative humidity is a nonlinear function of elevation, SCALMET uses the dewpoint temperature for the elevation adjustments, as this temperature is relatively linearily related to elevation. This can be done in analogy to temperature adjustments using monthly dewpoint temperature lapse rates (Liston & Elder 2006).

To distribute incoming shortwave and longwave radiation, two separate radiation models have been implemented in SCALMET. The potential incoming shortwave radiation at a specific place and time is calculated as a function of the solar zenith angle and topographic slope and aspect. To account for scattering, absorption and reflection of solar radiation in the atmosphere, climate model cloud cover is used to reduce available shortwave radiation and to discern the radiation in direct and diffuse parts.

Incoming longwave radiation is calculated following Liston & Elder (2006) and Iziomon et al. (2003). The core of the approach consists of the Stefan-Boltzmann law while taking into account cloud cover and elevation-related variations of atmospheric emissivity.

To account for wind speed dependence on elevation, high-resolution MM5 simulations (200 x 200 m) covering the area of the National Park Berchtesgaden in Germany have been statistically analysed. The analysed database consists of 115 datasets containing simulations for 72 wind directions and 9 combinations of wind speeds at 700 hPa and sea level. The resulting logarithmic wind speed function is implemented in SCALMET to allow wind speed adjustments in mountainous terrain. Surface pressure elevation corrections are performed using the hydrostatic barometric formula for isotherm conditions. Having distributed all meteorological variables as described above, the resulting meteorological fields need to be corrected to maintain the amount of mass and energy exchanged between the model scales. For this purpose equation 5 and the described subsequent steps have to be applied.

3.4 Upscaling of land surface simulations

Compared to the complexity of downscaling climate model outputs, the process of upscaling land surface model outputs is rather simple. To supply aggregated surface fluxes, SCALMET computes the mean subgrid-cell flux following equation 5.

4 Results and discussion

SCALMET includes physically realistic methods to scale climate model outputs. Although some approaches simplify the natural system, they partially allow the compensation of missing environmental variability in the climate models that result from coarse model resolutions. The following illustrations focus on temperature distributions, since temperature belongs to the key parameters of climate change. The analysis of the REMO A1B scenario run data shows a rise in the area averaged mean annual temperature for the Upper Danube river catchment of about 1.7°C for the time period from 2001 to 2050. As climate model simulations cover large areas with just one gridbox, the simulated mean conditions underestimate temperatures in lower elevations and overestimate temperatures in higher elevations. Direct interpolation methods are not capable of compensating this effect. Figure 3 shows the spatially distributed average air temperature inside the upper Danube river catchment for the year 1980.

These temperature distributions result from two remapping methods applied on REMO (Climate Of The 20th Century Run) data (Jacob 2001). The model run covers the time from 1950–2000 and is forced by simulated ECHAM data at the boundaries of the model domain. As the objective of this run is not to reproduce the specific conditions for a certain year but to produce a statistically consistent climate over a large period of time, temperatures are not to be compared with measured climate data for the year 1980. Nevertheless, the illustrations show some elemental characteristics of the applied remapping methods.

Not producing significantly different temperature extremes over the investigation area, the application of temperature lapse rates much better accounts for subgrid orographic variability. This can also be seen in figure 4. The illustration shows an elevation profile in combination with temperature profiles from Reutte to Imst, both located in Austria (black dots in figure 3).

While an increase in elevation for the application of temperature lapse rates leads to a decrease in temperature, bilinear interpolation leads to a considerable smoothing over several grid cells, which may be satisfactorily for larger scale investigations,

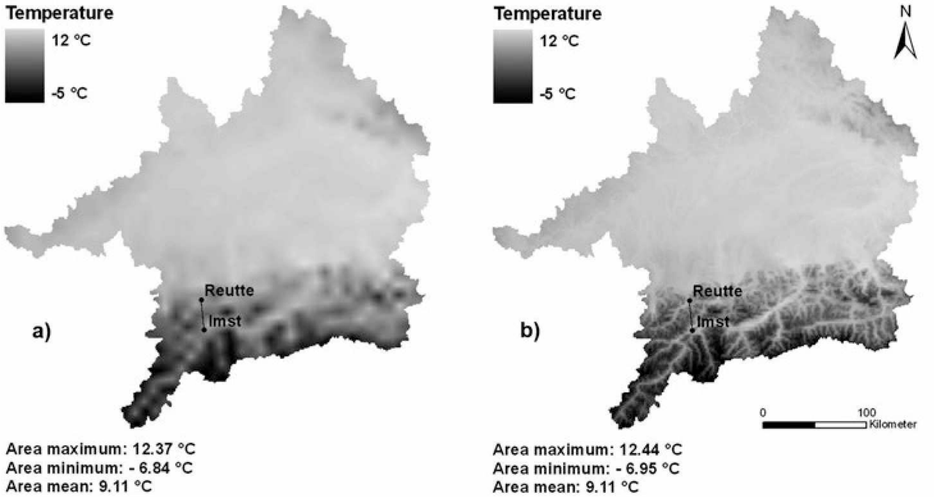

Figure 3: Average air temperature in the Upper Danube River Catchment in a spatial resolution of 1 x 1 km as a result of bilinear (a) and lapse rate remapping (b) of REMO simulations (10 x 10 km).

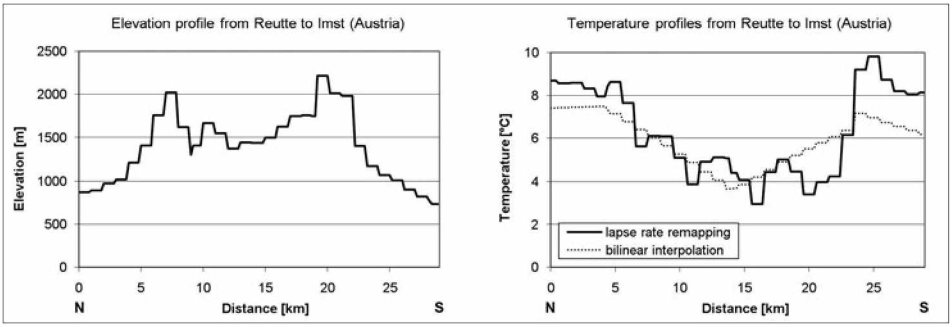

Figure 4: Elevation profile (left) and temperature profiles (right) from Reutte (N) to Imst (S). The temperature profiles are derived from remapped REMO data.

but does not represent the small-scale variability needed for local and single-catchment studies.

As shown above, to adequately remap climate model outputs is necessary to guarantee optimal land surface model results. The application of the described methods in coupled model runs is the subject of current work. Hydrological model results will show inaccuracies resulting from both, uncertainties in the meteorological model data itself as well as error ranges in the applied downscaling techniques. By using different regional climate models (REMO, MM5 and CLM) and different IPCC climate scenarios (A1B, B1 and A2) as meteorological input, a sensitivity analysis of the land surface model to changing meteorological boundary conditions is possible.

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References

Böhm, U., M. Kücken, W. Ahrens, A. Block, D. Hauffe, K. Keluer, B. Rockel & A. Will 2006, *CLM – the climate version of LM: Brief description and long-term applications*, COSMO Newsletter 6

Früh, B., J.W. Schipper & V. Wirth 2006, "A pragmatic approach for downscaling precipitation in alpine-scale complex terrain", *Meteorologische Zeitschrift 15,* 631–646

Grell, G.A., J. Dudhia & D.R. Stauffer 1994, "A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)", *Tech. Note NCAR/TN-398+STR National Center for Atmospheric Research,* Boulder, 138 pp.

Iziomon, M.G., H. Mayer & A. Matzarakis 2003, "Downward atmospheric longwave irradiance under clear and cloudy skies: Measurement and parameterization", *Journal of Atmospheric Solar-Terrestrial Physics 65*, 1107–1116

Jacob, D. 2001, "A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin", *Meteorology and Atmospheric Physics 77,* 61–73

Jones, P. 1998, "First- and Second-Order Conservative Remapping Schemes for Grids in Spherical Coordinates", *Monthly Weather Review 127*, 2204–2210

Liston, G. & K. Elder 2006, "A Meteorological Distribution System for High Resolution Terrestrial Modelling (MicroMet)", *Journal of Hydrometeorology 7*, 217–234

Mauser, W. & R. Ludwig 2002, "GLOWA-DANUBE – A research concept to develop integrative techniques, scenarios and strategies regarding the global change of the water cycle, in: Beniston M. (ed.), *Climatic Change: Implications for the hydrological cycle and for water management. Advances in Global Change Research No.10,* Boston, 171–188

Thornton, P.E., S.W. Running & M.A. White 1997, "Generating surfaces of daily meteorological variables over large regions of complex terrain", *Journal of Hydrology 190*, 214–251

WorldClim database 2007, on: http://www.worldclim.org (10.09.2007)