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Analysis of feedback effects and atmosphere responses when 2-way coupling a hydrological land surface model with a regional climate model – a case study for the Upper-Danube catchment

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Abstract

Most land surface hydrological models (LSHMs) take land surface processes (e.g. soil-plant-atmosphere interactions, lateral water flows, snow and ice) into detailed spatial account. On the other hand, they usually consider the atmosphere as exogenous driver only, thereby neglecting feedbacks between the land surface and the atmosphere. Regional climate models (RCMs), on the other hand, generally describe land surface processes much coarser but naturally include land-atmosphere interactions. What is the impact on RCMs performance of the differently applied model physics and spatial resolution of LSHMs? In order to investigate this question, this study analyses the impact of replacing the land surface model (LSM) within a RCM by a LSHM.

Therefore, a 2-way coupling approach was applied for a full integration of the LSHM PROMET ($1 \times 1\,\mathrm{km}^2$) and the atmospheric part of the RCM MM5 ($45 \times 45\,\mathrm{km}^2$). The scaling interface SCALMET is used for down- and upscaling the linear and non-linear fluxes between the model scales.

The response of the MM5 atmosphere to the replacement is investigated and validated for temperature and precipitation for a 4 yr period from 1996 to 1999 for the Upper-Danube catchment. By substituting the NOAH-LSM with PROMET, simulated non-bias-corrected near surface air temperature significantly improves for annual, monthly and daily courses, when compared to measurements from 277 meteorological weather stations within the Upper-Danube catchment. The mean annual bias was improved from −0.85 K to −0.13 K. In particular, the improved afternoon heating from May to September is caused by increased sensible heat flux and decreased latent heat flux as well as more incoming solar radiation in the fully coupled PROMET/MM5 in comparison to the NOAH/MM5 simulation. Triggered by the LSM replacement, precipitation overall is reduced, however simulated precipitation amounts are still of high uncertainty, both spatially and temporally. The distribution of precipitation follows the coarse topography representation in MM5, resulting in a spatial shift of maximum precipitation northwards the Alps. Consequently, simulation of river runoff inherits precipitation

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biases from MM5. However, by comparing the water balance, the bias of annual average runoff was improved from 21.2 % (NOAH/MM5) to 4.4 % (PROMET/MM5) when compared to measurements at the outlet gauge of the Upper-Danube watershed in Achleiten.

1 Introduction

Land surface models designed for hydrological studies (LSHMs) need meteorological data as input in order to simulate the pathway of water and energy at the land surface. This can be provided by measurements or regional climate models (RCMs). The latter is often used for hydrological impact studies on climate change scenarios. However, most LSHMs consider the atmosphere as an exogenous model driver only, applying a 1-way coupling approach and usually a correction of the systematic biases of temperature and precipitation (Marke et al., 2011a; Senatore et al., 2011), when driving LSHMs with data provided by a RCM (see Fig. 1). Thereby, the 1-way coupled model chain includes redundancy of two different land surface models, describing the same land surface processes. By not allowing for feedbacks between the downstream LSHM and the atmosphere of the RCM, inconsistencies occur when driving the LSHM offline with RCM output (Zabel et al., 2012).

Physically based LSHMs are usually designed to simulate small scale river basins on high spatial resolution, which allows for modelling physical processes with high process and spatial detail. They have intensely been validated reproducing gauge measurements and have recently extended from small to large scale river basins in the order of 1 million km^2 (Mauser and Bach, 2009; Ludwig et al., 2003). However, they go beyond reproducing runoff at gauges of small scale catchment areas and now consider in detail land surface processes (Garcia-Quijano and Barros, 2005; Kuchment et al., 2006; Kunstmann et al., 2008; Ludwig and Mauser, 2000; Mauser and Bach, 2009; Schulla and Jasper, 1999). The physically based models aim at understanding the interactions between the different land surface compartments, namely soil, vegetation,

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snow and ice in producing the resulting river runoff. Some are not calibrated with measured runoff and, thereby, in a strict sense, they conserve mass and energy at the land surface. They include detailed descriptions of vertical and lateral soil water and energy flows, vegetation dynamics and related flow regulations, snow and ice dynamics as well as energy and mass exchange with the atmosphere and, accordingly, land surface processes in the soil-plant-atmosphere continuum. However, for modelling runoff over mountainous terrain with RCM forcing adequately, a bias correction of the RCM data is necessary (Marke et al., 2011b).

On the other hand, LSMs designed for the use within RCMs, developed from coarse spatial resolution on continental scales, use a comparatively simple physical description of the land surface processes with simple parameterizations, in order to keep computational demand low (Chen and Dudhia, 2001; Henderson-Sellers et al., 1995, 1996; Pitman, 2003; Pitman and Henderson-Sellers, 1998; Wood et al., 1998). During the past years, they have become more and more complex, considering vegetation dynamics, biogeochemical processes, surface and subsurface hydrology, dynamic development of snowpack and include representations of urban and artificial areas as well as lakes (van den Hurk et al., 2011). Due to the latest developments, LSM and LSHMs overall seem to converge in terms of their physical skills. Nevertheless, a gap remains between the spatial resolution of RCMs and LSHMs. Therefore, we investigate the impacts of directly coupling a high resolution LSHM with a low resolution RCM using an appropriate up-and downscaling approach.

As shown in multiple studies, an improvement of physical parameterization and spatial resolution in RCMs is supposed to improve simulation results (Hagemann et al., 2001; Zängl, 2007a). 2-way coupling a LSHM with a RCM potentially seems to be a very powerful approach (Chen and Dudhia, 2001). Mölders and Raabe (1997) e.g. applied a 2-way coupling approach for a 24 h weather prediction forecast for a small domain of 225×150 km^2. Simulating large scale watersheds and longer time periods could not be considered at that time due to computational limitations. The central question concerning this study is, weather RCMs could benefit in terms of an improved modelling

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of atmospheric and land surface processes (e.g. temperature, precipitation, evapotranspiration, and runoff) from the spatially and process-wise more detailed land surface description when substituting the LSM of the RCM with a high spatial resolution LSHM and a spatial scaling mechanism.

In this study we take the Upper-Danube catchment ($A = 77\,000\,\text{km}^2$) over a 4-yr period from 1996–1999 to compare simulation results of atmospheric and land surface hydrology variables and simulated water balance with measurements, using the original MM5-NOAH and a replacement of NOAH with the high resolution PROMET-LSHM and a bi-directional scaling interface.

2 Materials and method

The RCM applied in this study is the fifth-generation Mesoscale Model (MM5) (Grell et al., 1994), developed by the Pennsylvania State University (Penn State) and the National Center for Atmospheric Research (NCAR). It was modified and adapted to our specific simulation requirements and our specific model domain (Pfeiffer and Zängl, 2009; Zängl, 2002). MM5 is used in climate mode with a horizontal spatial resolution of 45 km and an internal time step of 135 s. ECMWF ERA-40 reanalysis-data (Uppala et al., 2005) are used to nudge the double-nested MM5 model solutions 6-hourly at the lateral boundaries of the first nesting domain that covers the European continent with 79 grid-boxes in west-east and 69 grid-boxes in south-north directions (Pfeiffer and Zängl, 2009).

The NOAH-LSM (Chen and Dudhia, 2001) as an integral component of MM5 is an advanced physically based LSM designed for the use in atmosphere application such as MM5 and, thus, it uses the same spatial resolution than the atmosphere model. It has been developed with the goal of a simple but robust parameterization, taking the most important aspects of land surface hydrology into account (Chen and Dudhia, 2001). As a physically based LSHM, PROMET uses a more hydrological view on the land surface with a more detailed spatial resolution of 1 km and different physical

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formulations than the NOAH-LSM (Zabel et al., 2012). Detailed model descriptions of PROMET can be found in (Mauser and Bach, 2009; Muerth and Mauser, 2012).

An enhanced 2-way coupling approach, which takes care of the different spatial resolutions of the two components is used in this study for fully coupling the LSHM PROMET with the RCM MM5 for the model domain of Central Europe (Zabel et al., 2012). Therefore, the NOAH-LSM is replaced with PROMET and the bi-directional scaling tool SCALMET (Zabel et al., 2012). Thus, PROMET results of scalar surface fluxes, which are latent and sensible heat, short- and longwave outgoing radiation and momentum, are linearly upscaled to 45 km. These upscaled fluxes serve as the lower boundary conditions for the MM5 atmosphere and, consequently, MM5 results downscaled to 1 km provide the inputs to PROMET (Zabel et al., 2012). Besides, the non-scalar radiation temperature at the surface or at the top of the vegetation canopy respectively is given to MM5, since it is needed for initializing the convection scheme at each coupling time step. It is calculated from the upscaled emissivity and the upscaled emission of longwave radiation of the PROMET land surface using the Stefan-Boltzmann-law. The adjustable coupling time step for exchanging the fluxes between both models in both directions was set to 9 min in the current study. This allows PROMET to run synchronously with MM5, which uses an internal time-step of 135 s.

SCALMET assures the conservation of mass and energy during the up- and downscaling process. In order to guarantee for a consistent coupling between the models, a bias correction is not applied in this study. Further, PROMET maintains mass and energy at the land surface and is not calibrated with measured discharges.

A more detailed model comparison between PROMET and NOAH and methodological explanation of the coupling approach between PROMET and MM5 is given in Zabel et al. (2012). Within this paper, the results of three different configurations are compared with measurements (see Fig. 1):

- NOAH fully, interactively coupled with the atmospheric part of MM5.

- PROMET offline driven with MM5 output.

– PROMET interactively (bi-directionally) coupled with MM5, applying the 2-way coupling approach.

All simulation results are compared with measurements from 277 meteorological weather stations, spatially interpolated to the Upper Danube catchment. The catchment is situated in Central Europe, has an area of 76 653 km^2 and is characterized by a complex terrain, covering parts of the Alps in Southern Germany, Austria, Switzerland and Italy. Altitudes reach from 4049 m a.s.l. at Piz Bernina to 287 m a.s.l. at the catchment's outlet at the gauge in Achleiten. The lowlands north of the Alps are characterized by heterogeneous land and soil patterns, intense agriculture and high population density. The prevailing climate is characterized by the temperate latitudes with an annual precipitation gradient ranging from 550 mm in the Northern part of the catchment to more than 2000 mm in the Alps.

3 Results and discussion

3.1 Differences between PROMET and NOAH

As can be seen in Fig. 2, offline driven with RCM output, PROMET simulates less long-wave outgoing radiation and more short-wave outgoing radiation than NOAH. The lower long-wave outgoing radiation is mainly due to lower values of land surface emissivity within the PROMET parameterization than within the NOAH parameterization, while the higher amount of reflected short-wave radiation mainly results from a more heterogeneous land use and land cover in PROMET, having a higher number of land use/cover classes with high albedo values, such as urban area or rock. Further, snow cover increased short-wave reflection especially from March to May due to a spatially more detailed underlying topography, resulting in higher elevations in the Alpine area. In the PROMET simulation, snow cover still was predominant in the higher altitudes in May, while the high altitudes are averaged out in the NOAH topography due to the coarse spatial resolution.

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Overall, net radiation for the Upper-Danube catchment is higher by $8\,\mathrm{W\,m^{-2}}$. This net radiation is further differently distributed into latent and sensible heat due to different assumptions in the model's underlying land surfaces in terms of topography, soil and land use/cover properties (Zabel et al., 2012). Further, evapotranspiration is considerably lower due to impervious surfaces, such as urban area and rock that do not contribute to transpiration in PROMET while NOAH mainly implements a mixture of cropland and forest (Zabel et al., 2012) for the Upper-Danube. Consequently, sensible heat is higher in summer but lower in the winter months (Fig. 2) due to snow cover effects in the PROMET simulation in the Alpine area. While energy goes into snow melt instead of into sensible heat in the PROMET simulation, available net radiation has to become sensible heat in the NOAH-LSM. The higher spatial resolution in PROMET results in a more detailed modelling of the snow cover, especially in the spatially heterogeneous Alps with strong impact on the sensible heat flux. Thus, more energy goes into snow melt in the PROMET simulation, which explains the overall lower heat fluxes in the PROMET simulation although net radiation is a little higher.

3.2 Atmosphere responses

By replacing NOAH with PROMET and a bi-directional scaling interface, a full interactive coupling with the atmospheric part of MM5 is achieved and the modelled atmosphere responds to the replacement of the LSM.

3.2.1 Planetary boundary layer

Due to the tendency of higher sensible heat flux without snow cover in the PROMET model, the height of the planetary boundary layer is increasing in the PROMET/MM5 bi-directional coupling in summer and decreasing in winter over the Upper-Danube catchment. Consequently, this has far-reaching implications to the moisture content of air masses as well as the stability of stratification. Sensible heat is a sensitive parameter, affecting cloud fraction, convection and, thus, precipitation as well as solar radiation.

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In our setup, MM5 uses the Kain-Fritsch-2-scheme which turned out to be the best parameterization of the convection scheme for the simulation area, being tested with the NOAH-LSM with respect to simulated rainfall amounts (Pfeiffer and Zängl, 2010). This scheme was further applied to the PROMET/MM5 simulation, without adaptation and without testing other convection parameterization schemes in combination with PROMET.

3.2.2 Solar incoming radiation

Total incoming radiation, as the sum of direct and diffuse radiation, increases by the use of the PROMET land surface from 106 $W m^{-2}$ (NOAH) to 112 $W m^{-2}$. Measurements of radiation (117 $W m^{-2}$) calculated via the proportion of cloud cover from 277 meteorological stations are compared to simulation results in Fig. 4. The monthly incoming short-wave radiation is increased in the summer months and, thereby, closer to the measurements while the influence of the land surface on the atmospheric conditions is low in winter. The basic shape of the PROMET and NOAH curves is similar since it is mainly controlled by the passing low-pressure systems imposed onto the simulations by the ERA-40 lateral boundary forcing.

3.2.3 Temperature

The higher solar incoming radiation as well as lower evaporative cooling in PROMET results in an increase of the annual mean near surface air temperature from 5.93 °C to 6.65 °C in the fully coupled PROMET/MM5 simulations. The increase mainly occurs North of the Alps and near the city of Munich (Fig. 5). Measurements from 277 meteorological weather stations show 6.78 °C for the Upper-Danube catchment and the respective years. Thus, annual bias could be reduced from −0.85 K to −0.13 K. In addition, the monthly behaviour was improved in fully coupled PROMET/MM5 simulations when compared to measurements (see Fig. 6).

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Figure 7 shows the simulated diurnal cycle of the near surface air temperature for NOAH/MM5, PROMET/MM5 and measurements respectively. The impact of the land surface is marginal in the winter months due to low energy inputs on the land surface. Therefore, the bi-directional coupling approach with PROMET has almost no effect on the air temperature in the winter months. On the contrary, the diurnal cycle is strongly affected by the changed land surface in the summer months. Here, by using PROMET, near surface air temperature heats up faster and stronger. A cold bias of up to 2 K in the NOAH/MM5 simulation, especially in the afternoon hours in summer, corresponds to the results of Pfeiffer and Zängl (2009). Compared to measurements, a clear improvement can be investigated from May to September, where the diurnal course and particularly the maximum can be reproduced considerably better.

In August e.g., the mean maximum temperature is measured at 19.7 °C. While the NOAH/MM5 simulations only reaches 16.9 °C in the afternoon hours, the changed lower boundary conditions lead to a mean maximum daily temperature of 19.0 °C in bi-directionally coupled PROMET-MM5 simulations.

3.2.4 Precipitation

The measured annual precipitation for the area of the Upper-Danube is 1045 mm. While the NOAH/MM5 approach calculated 1180 mm, the fully coupled PROMET/MM5 approach simulated 1095 mm. Thus, annual bias was reduced from 12.9 % to 4.8 %. In particular, winter and spring precipitation is clearly overestimated (Fig. 8) in both MM5 simulations. However, precipitation amounts are reduced in the summer months as a respond of coupling the PROMET land surface with MM5, while winter and spring precipitation hardly changes (Fig. 8).

The decrease of monthly precipitation from May to September in the results of PROMET/MM5 is mainly due to the decrease of convective precipitation by 20 %, while non-convective precipitation is reduced by 9 % (Fig. 8). Therefore, it can be pointed out that the change of the land surface predominantly affects convective precipitation that finally decreases during summer for the Upper-Danube catchment. This results in an improvement for June and August but not in May and July.

However, heavy precipitation events such as in May 1999 due to special weather conditions are not properly reproduced in the Upper-Danube in both simulations where heavy precipitation is generally underestimated (Zängl, 2007b).

Further, Zängl (2007a) found a resolution-dependence, drastically affecting the MM5 model skill in the Alpine part of the model domain. By refining the mesh size from 9 km to 1 km, simulated precipitation could be considerably improved, due to a better representation of the topography in the atmosphere model. However, the coarse resolution of MM5 in our study (45 km) is not suitable for reproducing precipitation properly in the Alps and the foothills of the Alps. The coarse resolution of the MM5 topography results in a northwards shift of precipitation away from the Alps, when compared with measurements. Consequently, precipitation is overestimated in the Alpine foreland and underestimated in the Alps, due to leeward effects (see Fig. 9).

The use of PROMET instead of NOAH does not change the coarse resolution of the MM5 underlying topography. Therefore, the precipitation shift appears in both simulations while the annual overestimation in the alpine foreland is reduced in the PROMET simulations while at the same time the underestimation in the Alpine regions is increased. From this, we conclude that precipitation improved in the Northern part of the Upper-Danube catchment with low influence of the Alps and low relief.

Advective inflowing air masses passing the MM5 model domain, dominantly driven by the lateral boundary conditions (ERA-40), are one source of uncertainty, which ERA-40 data inherit to the RCM.

The coarse resolution of MM5 is another source for overestimating precipitation especially in winter, which coincides with the findings of Pfeiffer and Zängl (2010).

In addition, a systematic underestimation of wintertime snowfall in the observational dataset mainly in the Alpine domain should be considered in the evaluation.

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3.3 Feedback effects

3.3.1 Evapotranspiration

By coupling PROMET bi-directionally with MM5, simulated evapotranspiration increases between May and August and decreases slightly from September to April due to changed atmospheric conditions such as the increased temperature and solar radiation that feed back to the land surface in the bi-directional coupling case (Fig. 10).

Zabel et al. (2012) showed that the change of evapotranspiration in the fully coupled PROMET/MM5 simulations highly depends on the simulated soil moisture. Since wilting point is hardly ever reached in the Upper-Danube catchment, evapotranspiration is marginally affected by soil moisture and can thereby increase in summer.

3.3.2 Water balance

By the use of PROMET's baseflow, interflow and surface runoff as well as channel hydraulics components, simulated time series of monthly, daily and hourly runoff can be compared against hourly gauge measurements (Mauser and Bach, 2009). NOAH has the ability for modelling surface runoff formation but lacks in the option for simulating of lateral and river channel flow.

However, it is not the intention of this study to estimate the ability of bias corrected RCM inputs to reproduce runoff in the Upper Danube watershed. Since a bias correction would have been counterproductive in this study, biases of the RCM, particularly precipitation biases are handed over to the land surface components and, therefore, drastically affect runoff simulations.

Due to the coarse spatial resolution of 45 km in our study, the spatial patterns of precipitation follow the coarse spatial resolution of the underlying MM5 topography ($45 \times 45\,\text{km}^2$). The scale mismatch to the 1 km topography of PROMET, therefore, leads to inadequate spatial shifts and biases in runoff that cannot be corrected without a bias correction.

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Consequently, analogously to precipitation, a spatially detailed analysis of simulated river runoff underlies strong uncertainties in the Alps and the Alpine foreland. Nevertheless, regarding the annual water balance, simulated and annual averaged river runoff at the catchment's outlet was compared to the measured annual average runoff at the outlet of the Upper Danube Basin in Achleiten, which was determined to be 1412 $m^3 s^{-1}$ for the considered years. The results are shown in Table 1.

Mean surface runoff [mm] simulated by the NOAH-LSM for the Upper-Danube catchment and converted into the catchment's discharge, is 1712 $m^3 s^{-1}$. Thus, NOAH/MM5 strongly overestimates annual mean runoff. One way coupling of PROMET with MM5 results in a simulated average lateral river runoff of 1583 $m^3 s^{-1}$ and a considerable improvement from the NOAH/MM5 case. The full 2-way coupling of PROMET and MM5 leads to a simulated average river runoff of 1474 $m^3 s^{-1}$. This value can be considered to compare quite well with the observed 1412 $m^3 s^{-1}$. Thus, the annual bias could be reduced from 21.1 % (NOAH) to 4.4 % (2-way coupled PROMET).

4 Conclusions

In this study, we investigated the impacts of replacing the land surface module of the RCM MM5 with the LSHM PROMET for the Upper-Danube catchment. As shown, it is possible to use LSHMs embedded in RCMs, which offers new opportunities for both, the atmospheric and the hydrological community.

Through that replacement, the spatial resolution of the land surface representation improved from 45 km^2 to 1 km^2, which was dealt with by a bi-directional scaling interface that arranged the 2-way coupling between the models. It could be shown that different spatial scales and assumptions between the land surface models NOAH and PROMET lead to different simulation results of latent and sensible heat, as well as long- and short-wave outgoing radiation. Thereby, PROMET evapotranspiration was lower, while sensible heat flux tends to be higher. By applying the full 2-way coupling between PROMET and MM5, the atmosphere responded to the changed lower boundary

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conditions. As a consequence, mean annual temperature increased from 5.93 °C to 6.65 °C due to more incoming solar radiation and less evaporative cooling which lead to more sensible heat flux. Compared to meteorological measurements (6.78 °C), simulated near surface air temperature improved also for monthly and diurnal courses. Particularly afternoon heating was modelled more adequately by the use of PROMET. The impact of the PROMET land surface scheme on changes in the atmosphere is strongest in summer, when energy transformation at the land surface strongly affects atmosphere processes.

The impact on precipitation is difficult to diagnose, due to high uncertainties induced by the complex terrain of the catchment. Overall, precipitation was reduced mainly due to decreased convective precipitation in summer which can be explained by the rise of the planetary boundary layer due to more sensible heat flux. As a result, the moisture content of air masses is reduced and cloud fraction and convection are finally impeded. However, simulated precipitation shows a spatial shift northwards into the Alpine forelands when compared to measurements in the Upper-Danube catchment, as a result of the coarse description of the topography in MM5. The high temporal and spatial bias of precipitation, mainly in the Alps and the Alpine foreland is inherited to runoff simulation results in PROMET.

The NOAH river runoff for the Upper-Danube catchment converted from surface runoff [mm] was 1712 $m^3 s^{-1}$, which means a strong overestimation of annual runoff. Simulated annual river runoff improved to 1583 $m^3 s^{-1}$ when using the 1-way coupled PROMET/MM5 approach due to less precipitation and higher evapotranspiration. Finally, the fully coupled PROMET/MM5 approach improved the simulation of the outlet gauge in Achleiten to 1474 $m^3 s^{-1}$ without a bias correction in comparison to gauge measurements in Achleiten (1412 $m^3 s^{-1}$).

We conclude from these results that when comparing simulation results of an RCM using different land use schemes, all investigated meteorological and hydrological parameters improved in comparison with observations when moving from NOAH/MM5 to a fully-coupled PROMET/MM5.

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Table 1. Measured annual mean runoff at the outlet of the Upper Danube catchment at Achleiten in comparison with simulated runoff of NOAH/MM5 and PROMET/MM5 in either 1-way or 2-way coupled configuration.

Model Configuration	Runoff
NOAH	1712 $m^3 s^{-1}$
PROMET, 1-way coupled	1583 $m^3 s^{-1}$
PROMET, 2-way coupled	1474 $m^3 s^{-1}$
Measurements	1412 $m^3 s^{-1}$

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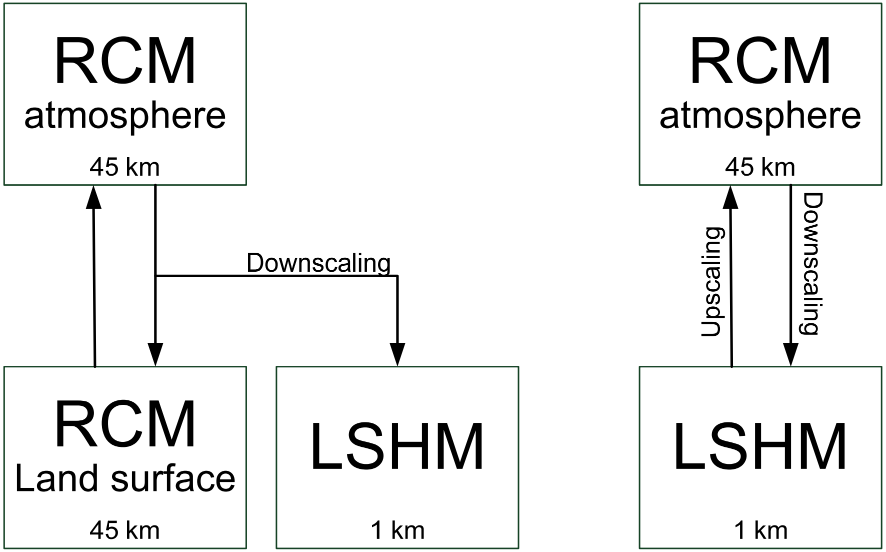

Fig. 1. Schematic illustration of 1-way (left) and 2-way coupling (right) a LSHM with a RCM.

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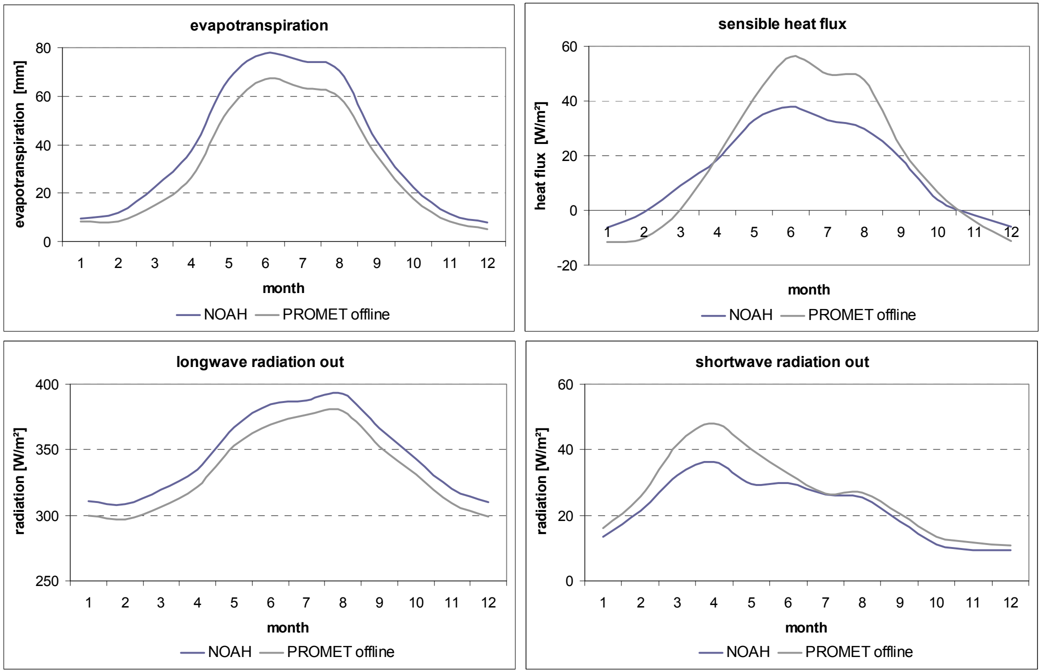

Fig. 2. Spatially averaged monthly land surface mass and energy fluxes (evapotranspiration, sensible heat flux, long-wave outgoing radiation, short-wave outgoing radiation) for the Upper-Danube catchment simulated with the NOAH-LSM and with PROMET offline respectively for the years 1996–1999.

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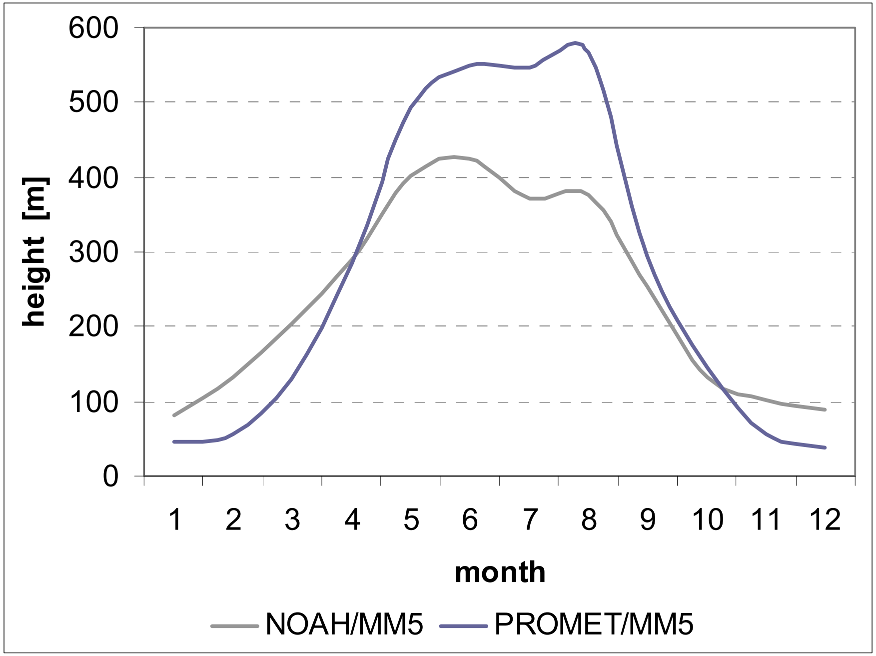

Fig. 3. Monthly course of the planetary boundary layer height (1996–1999).

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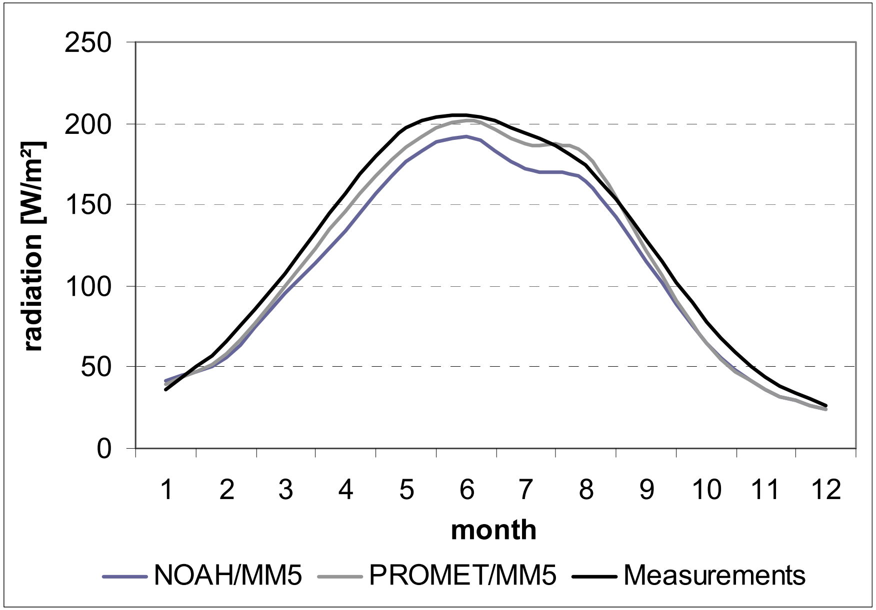

Fig. 4. Monthly course of the total incoming short-wave radiation (1996–1999).

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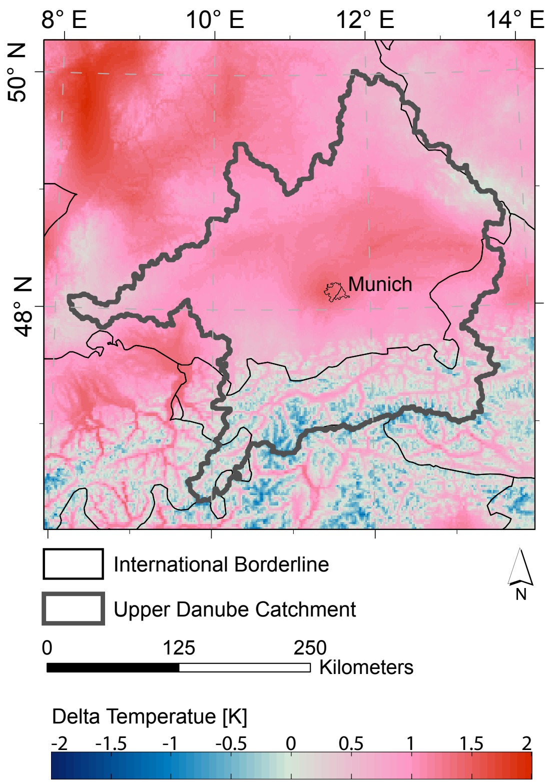

Fig. 5. Difference plot between PROMET/MM5 and NOAH/MM5 annual mean near surface air temperature in the Upper Danube Basin, downscaled to 1 km.

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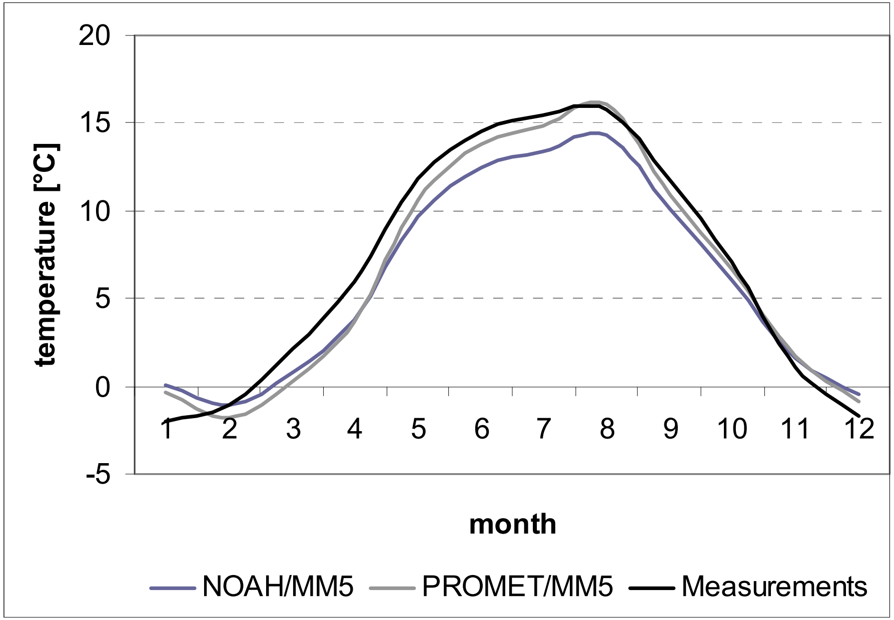

Fig. 6. Monthly mean temperature of fully coupled NOAH-MM5 simulation, PROMET-MM5 simulation in comparison with measurements in the Upper-Danube catchment.

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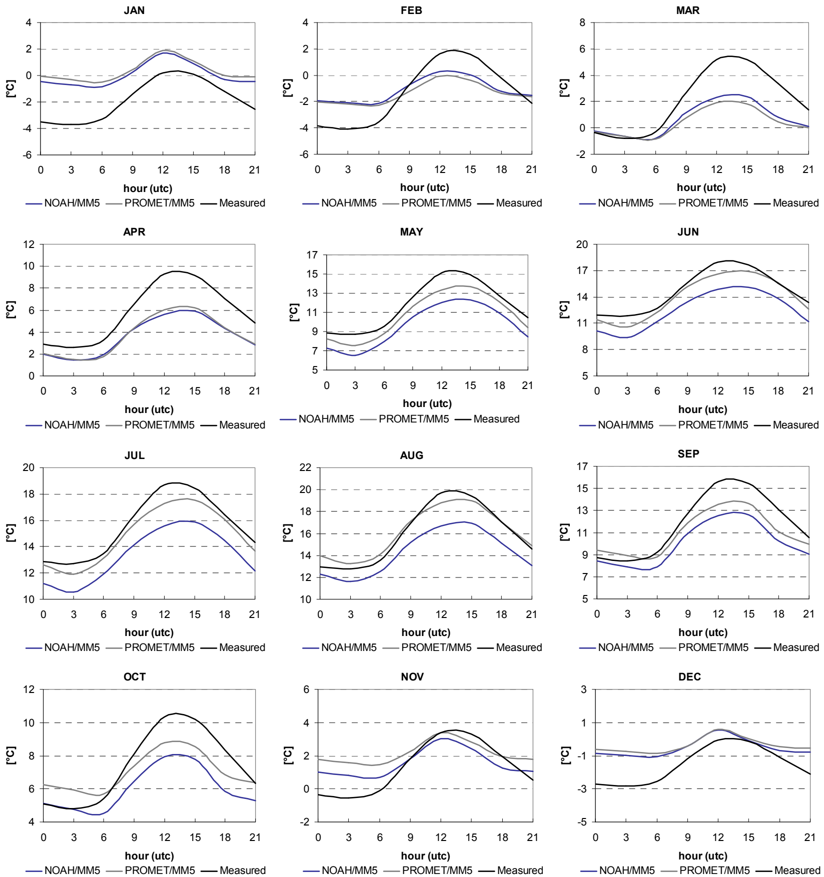

Fig. 7. Monthly mean diurnal cycle (1996–1999) of the near surface air temperature (3-hourly) for the Upper-Danube catchment.

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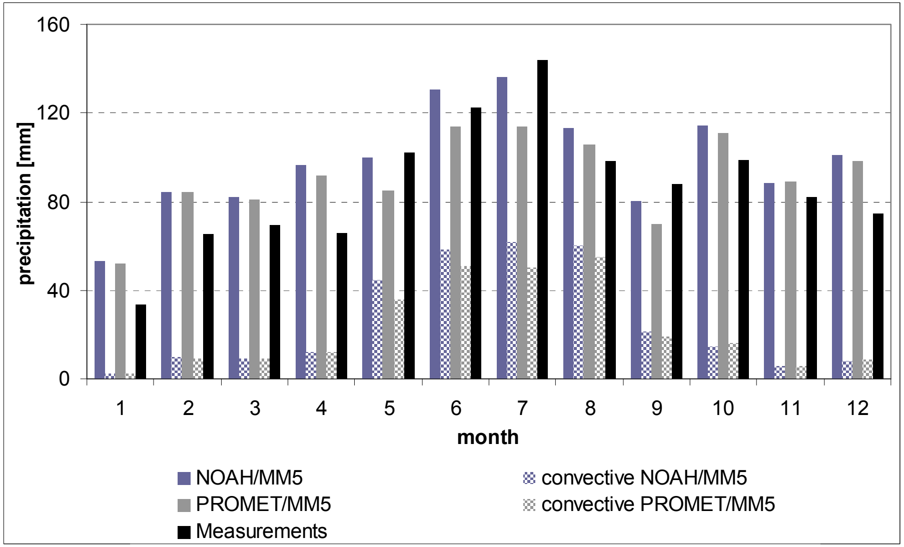

Fig. 8. Monthly convective and total precipitation of MM5 simulations coupled with NOAH and PROMET compared to measurements.

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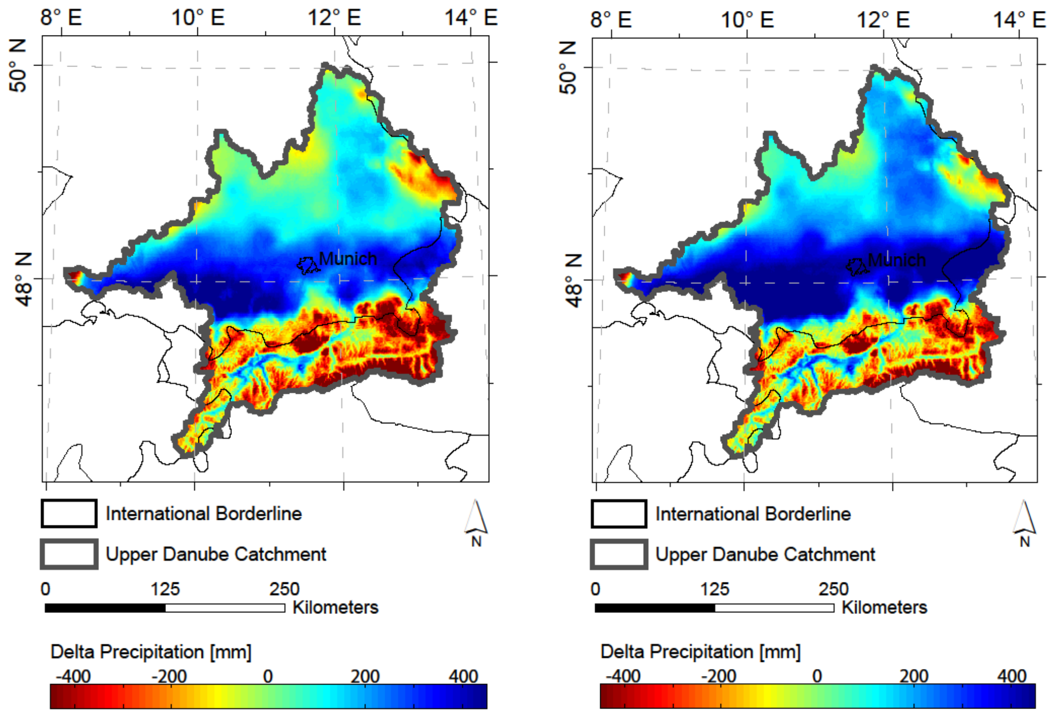

Fig. 9. Over- and underestimation of annual simulated PROMET/MM5 (left) and NOAH/MM5 (right) precipitation in the Upper Danube Basin, downscaled to 1 km and subtracted from measurements.

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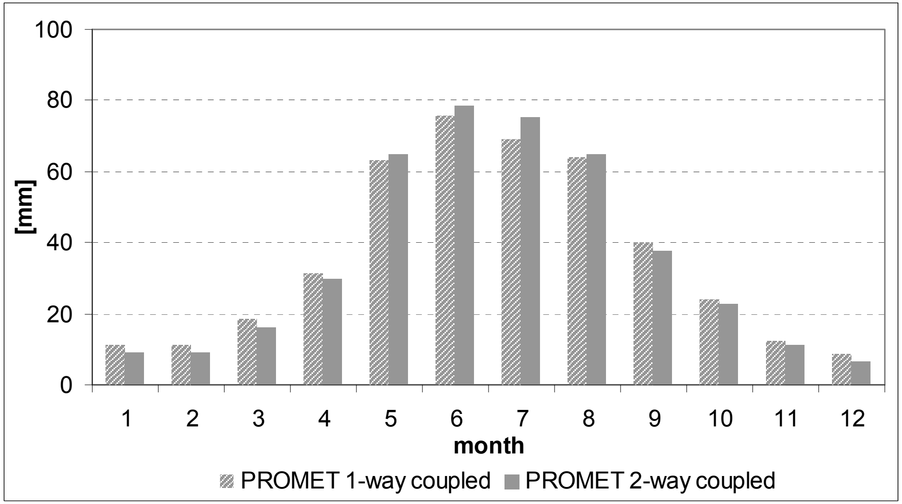

Fig. 10. Monthly mean evapotranspiration in the Upper Danube Basin of 1-way and 2-way coupled PROMET simulations (1996–1999).

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