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Modelling of snow processes in catchment hydrology by means of downscaled WRF meteorological data fields

K. Förster[1,2,3], G. Meon[1], and U. Strasser[2]

[1]Department of Hydrology, Water Management and Water Protection, Leichtweiss Institute for Hydraulic Engineering and Water Resources, University of Braunschweig, Beethovenstr. 51a, 38106 Braunschweig, Germany
[2]Institute of Geography, University of Innsbruck, Innrain 52f, 6020 Innsbruck, Austria
[3]alpS, Grabenweg 68, 6020 Innsbruck, Austria

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Correspondence to: K. Förster (kristian.foerster@uibk.ac.at)

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Abstract

Detailed physically based snowmelt models require a complete set of meteorological forcing data at the model's scale. Besides precipitation and temperature, time series of humidity, wind speed, and radiation have to be provided. The availability of these time series is in many cases restricted to a few meteorological stations and consequently, snowmelt modelling is often highly uncertain. To overcome this dilemma, the suitability of downscaled atmospheric analysis data for physically based snowmelt simulations in hydrological modelling is studied. We used the Weather Research and Forecast model (WRF) to derive spatial and temporal fields of meteorological surface variables as boundary conditions for four different snowmelt models. The simulations were carried out at the point scale and at the catchment scale for the Sieber catchment (44.4 km^2), Harz Mountains, Germany. For the latter, all snowmelt models were integrated into the hydrological modelling system PANTA RHEI. All models performed well at both scales. In conclusion, the presented approach is suitable to derive reliable estimates of snowpack and snowmelt processes as part of water balance and flood simulations for catchments exposed to snow.

1 Introduction

The water balance of mountainous or sub-arctic catchments is strongly influenced by snow cover processes. Due to accumulation of snow during the winter season, a considerable fraction of precipitation is stored in the snow pack. Rapid snowmelt, partially superimposed by rain events, can cause extensive flooding with potential of damage. Hence, hydrological modelling systems have to incorporate snow accumulation and melt for water resources management in regions that are affected by snow processes. In general, two types of snowmelt models are available:

– Temperature index model (also known as degree-day method) and extended index models (e.g., Anderson, 1973): these models are "simple and modest"

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(Rango and Martinec, 1995) because only temperature and precipitation time series are needed. Some extensions also incorporate shortwave radiation input (Hock, 1999; Pellicciotti et al., 2005).

- Energy balance models include a detailed physically based description for the surface energy balance of a snow pack (e.g., Anderson, 1968). The process based equations require further meteorological time series as input (e.g., humidity, radiation, wind speed). In contrast to index melt models, many more processes can be considered like sublimation losses, which can be relevant for the alpine water balance (Strasser et al., 2008). Even though some parameterizations of the energy balance can also be considered as inductive empirical functions (Beven, 2012), energy balance approaches are considered to be more reliable for scenario simulations than simpler index methods (e.g., Charbonneau et al., 1981; Pomeroy et al., 2007; Walter et al., 2005; Singh et al., 2009; Barry and Gan, 2011).

There are many physically based snowmelt models available for point scale applications (see, e.g., Etchevers et al., 2004; Rutter et al., 2009). Nevertheless, the temperature index method is widely accepted in hydrological modelling at the catchment scale (Rango and Martinec, 1995; Seibert, 1999; Beven, 2001). Moreover, apart from a few exceptions (Kuchment and Gelfan, 1996; Fuka et al., 2012), simple index approaches outperform energy balance approaches because the latter are more sensitive to the quality of meteorological input data (Zappa et al., 2003). Hence, "inadequate basin-scale hydrologic observations" (Franz et al., 2008) restricts catchment scale applications of energy balance approaches. This problem of "areal representativeness of point observations" (Klemeš, 1990) is mostly related to scaling issues (Blöschl and Sivapalan, 1995). In contrast to point scale considerations, regional applications (e.g., watershed hydrology at the catchment scale) require scaling approaches for observations and models because their scale triplets do not coincide in most cases (see e.g., Blöschl, 1999, for further details).

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Authors like Bales et al. (2006), Franz (2006), and Jost et al. (2012) suggest finding new strategies to provide suitable data to drive process based snowmelt models for catchment scale applications. For instance, Franz (2006) and El-Sadek et al. (2011) propose (re-)analysis data for hydrological modelling. However, this type of data does not provide a sufficient spatial and temporal resolution for typical applications in hydrological modelling. In consideration of topography, land use and soil type, regional models of the atmosphere that are also referred to as limited-area models (LAM) are suitable tools to "add regional detail" to these global scale (re-)analysis data (Giorgi, 2006). Besides hydrological forecasts and climate impact studies, successful applications of LAM in hydrological modelling and cryospheric research using (re-)analysis data were reported by Kunstmann and Stadler (2005), Rögnvaldsson et al. (2007a), Rögnvaldsson et al. (2007b), Bernhardt et al. (2010), Liu et al. (2011), Maussion et al. (2011), Pavelsky et al. (2011), and Mölg et al. (2012). In addition, globally available datasets can also be considered as valuable information for predictions for ungauged basins (Sivapalan et al., 2003) and ungauged climates (Merz et al., 2011).

In this study, a limited-area model of the atmosphere is applied to obtain hourly spatially distributed meteorological time series for snowmelt simulations at both the point and the catchment scale. It is assumed that the meteorological forcing data generated by a limited-area model by means of dynamical downscaling are physically consistent in space and time (Giorgi, 2006) – a basic requirement for physically based snowmelt models. As reported in the above-cited studies, analysis data are used herein as input for the LAM. In contrast or extension to other studies that address LAM input, four independent snowmelt models are applied at the point and at the catchment scale.

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2 Data and methods

2.1 Study area

All simulations were carried out in the Harz Mountains, a low mountain range in the northern part of Germany (see Fig. 1). The study area covers elevations ranging from 300 to 1100 m a.s.l. The Brocken (1142 m a.s.l.) is the highest peak of both the Harz Mountains and northern Germany. The Harz Mountains delineate the northern boundary of low mountain ranges in Germany merging into the North European Plain with elevations below 200 m a.s.l. Despite of the relatively low elevations, the climatological conditions are similar to those in the Bavarian Alps at elevation 2000 m a.s.l.

Due to altitudinal differences, considerable gradients in meteorological fields exist which reflect different climates. The mean annual temperature and precipitation depth at Clausthal climate station (585 m a.s.l.) are 6.2 °C and 1326 mm a^{-1}, respectively. However, the climate at the Brocken (1142 m a.s.l.) is considerably different (2.9 °C, 1814 mm a^{-1}). All values refer to the period 1961–1990.

Two sites were selected for the simulations in this study:

- Torfhaus meteorological station (805 m a.s.l.) for point scale applications: besides temperature and precipitation recordings, a snow lysimeter (2 m^2) is available to provide melt rates. Based on recordings from 2004 to 2012 the mean annual precipitation depth is approximately 1430 mm a^{-1}.

- Sieber catchment upstream of Pionierbrücke gauging station (340 m a.s.l.) for catchment scale applications: the upstream Sieber catchment covers an area of 44.4 km^2. Soil types of sandy loam and loamy sand over bedrock are prevailing. About 75 % of the catchment is covered by coniferous forest. Norway spruce (*Picea abies*) is the predominant wood species. The remaining parts of the area are covered by deciduous trees, meadows, upland moors, and minor settlements. Due to former mining activities in the Harz Mountains, a system of channels

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redirects water across the watershed boundary. This system of channels is part of the centuries old Upper Harz Water Management System, which has been declared a UNESCO world heritage site. The mean annual runoff depth for the period 1930–2008 is 1095 mm a^{-1}. Even though the average monthly precipitation depth is highest in December, the maximum value of mean monthly runoff depth typically occurs in April. This shift between the mean annual courses of precipitation and runoff depth can be related to snow accumulation during the winter and snowmelt in spring.

2.2 Selected winter seasons

Two winter seasons were selected from the last decade of observations with high temporal resolution for further investigations. The winter season 2005/06 was colder than average. This holds especially for the period from January 2006 until March 2006. Moreover, in February and March 30 % above average precipitation was recorded. With the beginning of April rapid snowmelt occurred due to significant rise in temperature accompanied by rain. On the contrary, the winter season 2010/11 differs with respect to timing of accumulation and melt. In December 2010 the observed temperature was 5 K colder than the average while precipitation was above average indicating ideal conditions for intensive snowfall. The highest daily snow depths in the second half of December observed at Clausthal for the period 1951–2011 were recorded in December 2010. In early January 2011 the weather changed and above average temperatures as well as rainfall were observed throughout the remaining winter season. In 2011 the spring was exceptionally dry and warm. It is assumed that these differences in meteorological boundary conditions are sufficient to fulfil the prerequisites of a differential split sample test (Klemeš, 1986). With this type of test different conditions for calibration and validation periods are presumed, and therefore, it “allows testing the “risky” predictions of a model rather than the “safe” ones” (Seibert, 2003).

2.3 Dynamical downscaling using WRF

In order to provide meteorological data fields with high resolution in space and time, a non-hydrostatic limited-area model (LAM) was applied. Warner (2011) states that for spatial resolutions of less than 10 km a non-hydrostatic model is necessary. The freely available LAM Advanced Research WRF (Weather Research and Forecast modeling system, Skamarock et al., 2008) was chosen for this reason. For convenience, this LAM is herein referred to as WRF.

A multi-nesting approach setup of the model was established to provide a spatial resolution of 1.1 km for the study area (see Fig. 2). The first domain ($\Delta x = \Delta y = 30$ km) covers central Europe bounded by the North Sea and the Baltic Sea to the north and the Alps to the south. Due to further refinements of the grid resolution major characteristics of the topography of the study area are captured in the fourth domain ($\Delta x = \Delta y = 1.1$ km).

The parameterization options of the model are listed in Table 1. A detailed description of the listed parameterization approaches can be found in the user's guide (Wang et al., 2012) or in the cited literature. Convection parameterizations are only applied to domain 1 and 2. Moreover, four-dimensional data assimilation (FDDA, Stauffer and Seaman, 1990) was activated to keep the longterm simulations close to the input data. This approach is proposed by Lo et al. (2008) although other approaches like the re-initialization are also common (Maussion et al., 2011; Hines et al., 2011).

Initial and boundary conditions were obtained from the NCEP FNL Operational Model Global Tropospheric Analyses dataset (ds083.2) using the WRF "Preprocessing System" (WPS) which is also described by Wang et al. (2012). This dataset contains major meteorological variables at the surface and mandatory vertical levels of the atmosphere on $1^\circ \times 1^\circ$ grids prepared operationally every six hours (NCEP, 2012a). Its temporal availability covers the range from July 1999 to present. To account for temperature changes in the North Sea and Baltic Sea, additional sea surface temperature data being available at daily grids with a spatial resolution of $0.5^\circ \times 0.5^\circ$

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(RTG-SST dataset, Thiebaux et al., 2003; NCEP, 2012b) were also prepared using WPS.

Finally, hourly gridded meteorological fields with grid spacings of 1.1 km were simulated using WRF for both the winter season 2005/06 and 2010/11. Surface meteorological variables that were derived in this manner are listed as follows: precipitation intensity, temperature (2 m), specific and relative humidity (2 m), wind speed (10 m), and shortwave as well as longwave radiation.

2.4 Snowmelt models

Three energy balance snowmelt models and the temperature-index method were tested at the point and at the catchment scale. All algorithms were originally available at the point scale. The following list accounts for the major characteristics of each model. The reader is referred to the cited literature for a detailed description. Due to the fact that the Sieber catchment is almost entirely covered by forests, the short descriptions emphasize the consideration of forest effects on the energy balance.

- The Utah Energy Balance Model Version 2.2 (Tarboton and Luce, 1996) is available as open source software and can be obtained via internet (Tarboton, 2012). Originally, the model was designed to carry out simulations for time steps of 1 and 6 h, respectively. Snow water equivalent and energy content are the prognostic variables calculated for each time step using a predictor corrector approach. The model accounts for liquid water and incorporates a simple approach to simulate the ground heat flux. Forest cover effects are represented by one single parameter that reduces wind speed and solar irradiance.

- ESCIMO (Energy balance Snow Cover Integrated MOdel, see, Strasser et al., 2002; Strasser and Marke, 2010) was originally developed for point scale applications. Later the model was extended to the fully distributed snow model AMUNDSEN (Alpine MUltiscale Numerical Distributed Simulation ENgine, Strasser et al., 2004), which includes detailed process descriptions, e.g.

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for topography-dependent radiative transfer, gravitational and wind-induced redistribution of snow, technical snow production or runoff concentration. For both models a detailed description for snow canopy interaction was added recently (Strasser et al., 2011). This approach adds subcanopy modifications to open-site meteorological conditions and incorporates a canopy interception model (Hedstrom and Pomeroy, 1998), which builds upon the scaling approach of Pomeroy and Schmidt (1993) and Pomeroy et al. (1998), for simulating the sublimation. The dependence of the leaf area index on the interception capacity is accomplished according to Liston and Elder (2006). All these processes were also successfully tested at the catchment scale (Warscher et al., 2013). In this study, the point scale model ESCIMO including the canopy model is used.

- Walter (2012) provides a spread sheet version of the algorithms described in Walter et al. (2005). The basic idea of their investigations was to develop a physically based alternative to the temperature index method without any additional data requirements. Regardless of its simplicity, the algorithm accounts for all relevant components of the energy balance as well as for liquid water storage and variable density. The original algorithm assumes daily time steps. In this study, all simulations were carried out for hourly time steps. Therefore, an adaption of the original algorithm was necessary. Only the radiation balance has been modified in this study. Instead of using daily minimum and maximum temperature as proposed by Walter et al. (2005), time series of shortwave and longwave radiation were used herein. Several equations like the albedo recession were adopted for hourly time steps. Like the Utah Energy Balance model the snowmelt model from Walter et al. (2005) accounts for forest canopy effects by providing one parameter to scale shortwave radiation.

- For reasons of comparability and because of its popularity, the temperature-index approach was also considered. Forest effects on snowmelt can be taken

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into consideration by calibration of the degree-day value that is typically lower in forests with respect to open sites.

In order to make the snowmelt models available for catchment scale applications, they have been implemented into a hydrological modelling system. This step is described in the next section.

2.5 Hydrological modelling

All simulations at the catchment scale were carried out using the hydrological modelling system PANTA RHEI for the Sieber catchment. PANTA RHEI has been developed by the Department of Hydrology, Water Management and Water protection, Leichtweiss Institute for Hydraulic Engineering and Water Resources, University of Braunschweig, in corporation with the Institut für Wassermanagement IfW GmbH, Braunschweig (LWI-HYWAG and IfW, 2012). At the moment, the model is used for a wide range of tasks in national and international projects:

- Science: longterm water balance simulations and optimization of reservoir cascade operation for climate change impact studies (Meon and Gocht, 2012).
- Engineering practice: integrated flood protection concepts, hydrological design floods for hydraulic structures.
- Engineering practice: online flood prediction of medium to small catchments, e.g. by the Flood Early Warning Centre of the German Federal State of Lower Saxony.

Since PANTA RHEI features a graphical user interface (GUI) and geographic information system (GIS) data exchange capabilities, it is a 4th generation hydrological modelling system according to the classification of Refsgaard (1996). With respect to the level of sophistication of processes PANTA RHEI is a conceptual deterministic modelling system although physically based enhancements exist like the energy balance snowmelt models described herein or, optional physically based algorithms

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for the evapotranspiration and the soil water balance (Förster et al., 2012; Kreye et al., 2012). It can also be characterized as a semi-distributed modelling system subdividing the watershed into highly resoluted sub-catchments and subsequently into hydrological response units (HRUs). The choice of the simulation time step depends on the task. Common settings range from minutes to one day. For flood simulations, one hour is a typical time step (LWI-HYWAG and IfW, 2012).

The vertical column of hydrological processes including snowmelt, interception, infiltration, and soil water are calculated for every HRU (Fig. 3). Runoff concentration (including several runoff components) and routing calculations are carried out for the entire sub-catchment presuming an aggregation of all associated HRUs. For this study we used the following configuration: the snowmelt models described in Sect. 2.4 have been integrated into the modelling system as individual components, each representing a fully functionable snowmelt model. It is assumed that the governing equations of micro scale processes are also valid for heterogeneous areal elements. Moreover, upscaling might also accompany changes in dominant hydrological processes. This leads physical parameters to become "effective" parameters (Kirchner, 2006). Their physical meaning might be blurred to some extent due to these uncertainties.

All other hydrological processes were not changed throughout the study. Interception is calculated according to the Rutter et al. (1971) model. Infiltration and the soil water balance were simulated in a simplified way using a modified curve number approach which was adopted for continuous simulations (Riedel, 2004). Potential evapotranspiration is derived using the Penman–Monteith method (Monteith, 1965). The calculation of actual evapotranspiration depends on the amount of intercepted water and soil water storage. For each HRU the runoff is subdivided into surface runoff, interflow, and base flow for each time step. A subdivision assuming two groundwater storages is also possible. Then these runoff components are aggregated to obtain the respective values for the superordinate sub-catchment. Routing is not only available for sub-catchments but also for reservoirs, retention structures, culverts and other features.

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A detailed hydrological model of the Sieber catchment for PANTA RHEI derived in an ongoing climate change research project was available for this study (Hölscher et al., 2012). The catchment was sub-divided into 73 sub-catchments which account for a mean area of 0.6 km^2. Redirections of water due to channels associated to the Upper Harz Water Management System were also considered presuming mean annual and seasonal flow rates. The calibration of the model was carried out using longterm simulations based on daily meteorological data ranging from 1971 to 2000 and hourly precipitation time series ranging from 2002 to 2008. The snowmelt models were calibrated separately using only the meteorological data from dynamical downscaling for the winter season 2005/06, whereas the winter season 2010/11 is viewed as validation period.

3 Results and discussion

3.1 Meteorological fields

In a first step, we compared the meteorological data fields derived by WRF with observations from meteorological stations. This comparison provides a first assessment of the accuracy of the dynamical downscaling of global atmospheric analysis data for the study area. In this paper, only precipitation and temperature time series are displayed. The obtained high accuracy of other meteorological variables is described by Förster (2013).

Figure 4 depicts the cumulative mean areal precipitation based on observations from the precipitation gauge network and the WRF simulations for the winter season 2005/06. The cumulative precipitation is derived by calculating the arithmetic mean of 19 stations and 19 corresponding grid points of the atmospheric model, respectively. These stations are situated in the Harz Mountains and its vicinity. The course (mass curves) of simulated precipitation coincides reasonably well compared to observations. However, the sum of simulated precipitation only accounts for 81 % of the observed areal mean. During the melt season, which falls at the end of March and the beginning of April 2006, simulated precipitation intensities are substantially lower than observed intensities. The correlation of six-hourly intensities is 0.66. The deviation between observed and simulated precipitation is obviously caused by uncertainties involved in the original analysis data and the downscaling process with regard to the heterogeneous orographic conditions of the small project region (upwind and downwind effects).

In general, temperature simulations match observations better than precipitation simulations do. The temperature time series of the WRF grid point that correspondents to the location of Torfhaus station was evaluated (Fig. 5). The simulated time series matches observations at Torfhaus very closely which is reflected in the high correlation of 0.93. Nevertheless, the statistics reveal that the simulation is biased towards colder temperatures. The mean simulated temperature is 0.7 K lower than the mean value (−1.2 K) of the observed time series. This becomes also evident when considering the underestimation of maximum temperatures as shown in Fig. 5.

All other relevant meteorological variables were also simulated well. As indicated above, the accuracy of the time series of precipitation was statistically reasonable but not sufficient to be used as an input into snowmelt and hydrological modelling in this context. Since precipitation intensity is crucial during rain on snow events, we decided to use observed precipitation time series for snowmelt simulations instead. However, temperature, humidity, wind speed, as well as shortwave and longwave radiation from WRF simulations were used for snowmelt calculations at both scales.

3.2 Point scale simulations

As described in the previous section, all relevant meteorological variables except for precipitation were used for snowmelt modelling on the basis of WRF simulations. The time series of the model grid cell corresponding to Torfhaus meteorological station were used as input for snowmelt modelling. All simulations were carried out using a time step of one hour for the entire winter season (1 November 2005–1 May 2006

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as well as 1 November 2010–1 April 2011). Figure 6 shows the results for the melt event in the spring of 2006 at Torfhaus (calibration period). For each snowmelt model simulated runoff as well as snow water equivalent time series are plotted. Every subplot shows the melt runoff recorded by the lysimeter. Cumulative runoff time series for both model and observation can easily be related to snow water equivalent and cumulative precipitation.

In total, all snowmelt models simulate the melt runoff well and in agreement with observations. Total melt as well as diurnal features are captured by all model simulations. All models tend to overestimate melt runoff during the first days of the melt event. The peak runoff at 31 March 2006 is also overestimated by all tested models. There is still a snow pack remaining in all simulation runs at the end of the melt event whereas the automated snow depth recordings indicate a complete ablation of the snow cover. In contrast, melt runoff was still observed even though no precipitation was recorded during this period. Hence, the results from the simulation runs seem to be realistic.

The validation of the models was performed using data of the winter season 2010/11 (Fig. 7). Modelled runoff melt time series coincide well compared to the recorded lysimeter observations. Especially the Utah Energy Balance Model and ESCIMO closely match observations.

Figure 10a illustrates a statistical summary of each point scale simulation run with respect to the recorded melt runoff time series. This type of diagram is described by Taylor (2001) and therefore herein referred to as Taylor diagram. Each point represents the model performance of one simulation run. Ordinate and abscissa refer to the standard deviation of the time series. The angle between the abscissa and the lines representing the shortest distance of each point to the origin is related to the correlation between observation and model run. The radial distance of each point to the origin represents the standard deviation of the model run. The geometric relationship of the Taylor diagram also incorporates the central pattern root mean square error (RMSE) between observation and model run which correspondents to the concentric isolines.

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These isolines are centered by the observation point. By definition the correlation of the observation is 1.0 and the RMSE is 0.0, respectively.

To conclude, the Taylor diagram enables a simple overview considering multiple simulation runs incorporating more than one statistical parameter for evaluation of model performance. In contrast to one single statistical parameter indicating model performance, it allows for determining whether the differences are caused due to phase shifts or disagreements in amplitudes (Taylor, 2001). Due to normalization of standard deviations (the standard deviation of the observation is set to unity), a comparison of simulation runs referring to different reference datasets (observations) is possible because the RMSE is also normalized by this procedure.

Values of correlation range from 0.67 to 0.95 for the selected snowmelt models (Fig. 10a). RMSE extends over the range between 0.3 and 0.8. The normalized standard deviation of the simulation runs ranges from 75 to 130 % indicating that some models underestimate the amplitude of melt runoff whereas others overestimate the variability. For instance, the overestimation of melt runoff calculated by ESCIMO in 2006 is reflected by relatively high values of RMSE and normalized standard deviation. However, the timing of the model is still good which is expressed in the high correlation value.

The results for the validation period (2010/11) are generally better. In total it is concluded, that the use of a snowmelt model clearly improves the simulation results. All snowmelt models show a better performance than the simple assumption that all precipitation throughout the winter is rain ("no snow"). Based on these results, the Utah Energy Balance Model seems to perform best at Torfhaus. The ranking of models should, however, be interpreted with caution because only two winter seasons were evaluated.

3.3 Catchment scale simulations

According to the previous section, all snowmelt models were likewise applied using PANTA RHEI for the Sieber catchment. For ESCIMO the canopy extensions were

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used for all areas covered by forests. All simulations cover the entire winter season as mentioned in the previous section. Calibrations were carried out for the winter season 2005/06. Again, only the snowmelt components were calibrated at this stage. The other components of the hydrological model like retention parameters and the soil model had already been calibrated independently using longer time series (Sect. 2.5).

Since three quarters of the Sieber catchment are covered by forest, an adaption to the point scale parameter sets was necessary. Thus, the calibration procedure focused on the consideration of these effects. The manual calibration of the Utah Energy Balance Model including the highest number of adjustable parameters was not easy. Several combinations of parameter settings including the choice of an appropriate forest cover fraction led to similar results which were all very good. This issue is related to the problem of equifinality which is inherent when adapting point scale equations to larger scales (e.g., Beven, 2002; Kirchner, 2006). In contrast to all other tested snowmelt models, ESCIMO includes a detailed model component to simulate snow processes in canopies (thus, the model is hereinafter referred to as ESCIMO + Canopy). This model utilizes the spatial distribution of LAI values in the Sieber catchment. These LAI values for several land use classes have been provided in terms of lookup tables that were derived from literature review (e.g., Breuer et al., 2003). Hence, ESCIMO + Canopy should account for the change in dominant processes due to upscaling, which includes, e.g., canopy effects on the energy balance when considering areal elements instead of idealized point scale considerations.

Figure 8 shows the results of each snowmelt model according to the previous section but for the entire winter season including the accumulation period. The simulated streamflow tracks the observed streamflow very well for all snowmelt models. Both the rain on snow event at the end of March to the beginning of April and the subsequent smaller flood in mid-April are simulated with high accuracy by all snowmelt models. The simulations of the first flood peak in December seem to be heavily dependent on how the model separates rain and snow. However, the snowpack evolution is simulated in accordance by all models. Because basin scale observations of snow water equivalent

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are not available, it is not clear which model is most accurate in simulating snowpack evolution.

The results of the validation period (winter season 2010/11) are shown in Fig. 9. The tested snowmelt models perform well compared to observations. The flood peak in January 2011 yielding $26\,m^3\,s^{-1}$ is underestimated by all models. It ranges from $14\,m^3\,s^{-1}$ (temperature index approach) to $19\,m^3\,s^{-1}$ (modified Walter approach). From Fig. 9 it can be seen that the observed as well as the simulated runoff depth exceed the observed areal precipitation which is also used as an input for all models used herein. Possible explanations for this mismatch could include a lack in representativeness of observed precipitation and streamflow data or even uncertainties related to the settings of initial conditions. However, the timing of snowmelt seems to be simulated well by all models.

Since basin scale snow water equivalent estimates were not available, statistics were prepared for streamflow time series. Figure 10b summarizes the statistical evaluation of all simulation runs for the Sieber catchment using a Taylor diagram. Since Fig. 10b is also normalized with respect to standard deviation and RMSE, a comparison with the point scale results (Fig. 10a) is possible. At first, the catchment scale results are discussed independently. Regarding the statistics from the Taylor diagram, the differences in performance parameters are small. For all model runs, except one, a correlation higher than 0.9 is achieved. RMSE values account for 0.25 to 0.5 times the standard deviation of the observation time series. All models perform clearly better than the "no snow" assumption and indicate the relevance of snow processes for the water balance of the Sieber catchment. It is worth to note that all energy balance approaches perform better than the proven temperature index approach whereas the modified Walter approach matches the patterns of observed time series best at this scale.

Obviously, the different ways in which forest effects are accounted for by the snowmelt models do not have a major impact on the results for the Sieber catchment simulations because all model simulations are in good agreement with observations.

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However, the explicit treatment of snow-canopy interaction as incorporated by ESCIMO + Canopy enables a more reliable simulation of sublimation in forests. Figure 11 shows the cumulative net water vapour mass flux of the Utah Energy Balance Model and ESCIMO + Canopy for both point and catchment scale applications, respectively. During the winter season a gain of water vapour is simulated at Torfhaus using both the Utah Energy Balance Model and ESCIMO (point scale). Highest condensation rates were simulated during the rain on snow event at the end of March and at the beginning of April, respectively. When using the Utah Energy Balance Model, a net water vapour gain of 15 mm for the entire Sieber catchment is calculated. With ESCIMO + Canopy, a net loss of water vapour of even 40 mm is calculated for the Sieber catchment although the results indicate condensation during the rain on snow event too. Sublimation losses can typically occur in forests due to the exposure of intercepted snow to higher turbulent exchange and higher solar radiation input when compared to beneath-canopy (turbulent exchange and shortwave radiation are reduced) and open site (turbulent exchange is in general lower due to lower roughness) conditions, respectively. Since ESCIMO + Canopy features these processes, the difference in Fig. 11 can be related to the different level of processes representation.

The point and the catchment scale results reveal that the differences in model performance are smaller for the catchment scale. At catchment scale many more hydrological processes have to be incorporated for the simulation rather than exclusively considering snowmelt processes at the point scale. Other hydrological processes become more dominant when scaling up from the point to the catchment scale. Typically, the relevance of snowmelt on floods decreases with an increase of scale.

When comparing the results from both scales in Fig. 10, it is interesting to note that the ranking of the energy balance models is in reverse order. As explained in the previous section, model ranking should be interpreted with caution due to the fact that only two sites and two winter seasons were considered for this study.

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4 Summary and conclusions

A dynamical downscaling approach using global atmospheric analysis data to force snowmelt models at different scales was tested. To derive meteorological data fields we applied the Weather Research and Forecast model (WRF) driven by NCEP analysis data. The meteorological fields including precipitation, temperature, humidity, wind speed, shortwave radiation, and longwave radiation were prepared as gridded datasets for hourly time steps. Four snowmelt models including three energy balance models were set up for point and catchment scale applications. For the latter, all energy balance approaches were added to the hydrological modelling system PANTA RHEI.

The meteorological data fields were extensively evaluated using time series from the existing meteorological station network. It was not possible to simulate precipitation time series with high accuracy at the considered scales. For the other relevant meteorological variables the simulated time series match surface observations better. Therefore, we decided to apply all meteorological variables as boundary conditions for snowmelt modelling at the point and the catchment scale, with the exception of precipitation. Instead, observed precipitation time series were used for that reason.

All snowmelt simulations perform well at both the point and the catchment scale. The statistical evaluation revealed that the snowmelt models consistently better match the observations if compared with the "no snow" assumption. These findings emphasize the need to include accurate snowmelt modelling for the study area including both point and catchment scale applications. In general, the differences in model performance are smaller at the catchment scale where other hydrological processes are also relevant. Although the detailed canopy model does not significantly improve snowmelt simulations, for other sites the total sublimation losses can exceed the relative low value of 5 % calculated for the Sieber catchment (see, e.g., Strasser et al., 2008). On the other hand, the problem of equifinality is evident when considering very complex physical models adapted to large scale applications. Several sets of effective parameters yield similar results when using the Utah Energy Balance Model with

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PANTA RHEI. Hence, scaling approaches according to Clark et al. (2011) should be considered.

Besides these scaling issues, the presented approach could be applied successfully. The meteorological fields derived from dynamical downscaling using WRF with analysis data match the observations well, except for precipitation. Furthermore, this study contributes to the ongoing discussion about the need for providing physically based modelling approaches in areas where only a few observations are available. In addition, physical models are said to be more reliable for meteorological conditions that are not covered by the datasets used for calibration. In conclusion, the presented approach might be suitable to derive reliable estimates on snow water resources in remote areas. Other fields of application could include snowmelt model inter-comparison studies at the catchment scale.

Acknowledgements. The meteorological data as well as the hydrological model of the Sieber catchment were provided by the KliBiW research project ("Global climate change and impacts to water resources management in Lower Saxony") which has been conducted in cooperation with the Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, NLWKN). This project was funded by the Ministry of the Environment of the German Federal State of Lower Saxony. The atmospheric analysis data are available online, provided by the National Centers for Environmental Prediction/National Weather Service/NOAA/US Department of Commerce. 2000, updated daily, see "NCEP FNL Operational Model Global Tropospheric Analyses, continuing from July 1999". Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. http://rda.ucar.edu/datasets/ds083.2, accessed 16 November 2012. Observed snow lysimeter time series were kindly made available by the Harzwasserwerke GmbH, Hildesheim.

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Table 1. WRF physics parameterization setup. Brief descriptions of the physics parameterizations are also given by Wang et al. (2012) and Skamarock et al. (2008).

Processes	Parameterization
Cloud microphysics	Morrison et al. (2009)
Convection	Kain–Fritsch scheme (Kain, 2004)
Boundary layer	Yonsei University scheme (Hong et al., 2006)
Land surface processes	Noah land surface model (LSM) (Chen and Dudhia, 2001)
Shortwave radiation	Dudhia (1989) scheme
Longwave radiation	Rapid Radiative Transfer Model (Mlawer et al., 1997)

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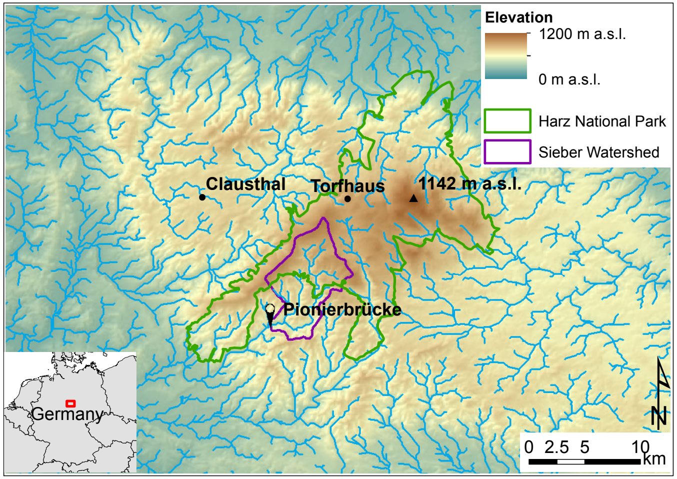

Fig. 1. Map of the study area including the Sieber catchment located in the Harz Mountains, northern Germany. The Harz National Park boundary is provided by OpenStreetMap, © OpenStreetMap contributors (http://www.openstreetmap.org/copyright).

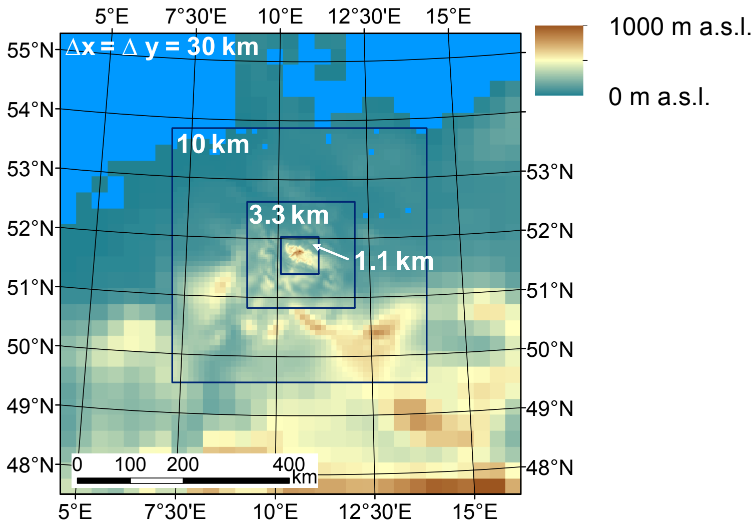

Fig. 2. WRF domains of the study area. The resolution of the first (outer) domain is 30 km, the fourth and final (inner) domain's resolution is 1.1 km, respectively.

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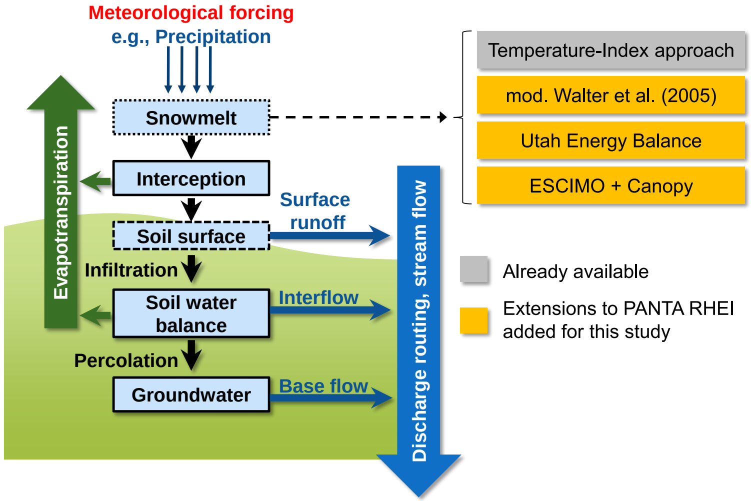

Fig. 3. Conceptualization of hydrological processes in PANTA RHEI (adapted from LWI-HYWAG and IfW, 2012). According to Sect. 2.4 each snowmelt model can be seen as alternative representation of the snowmelt processes.

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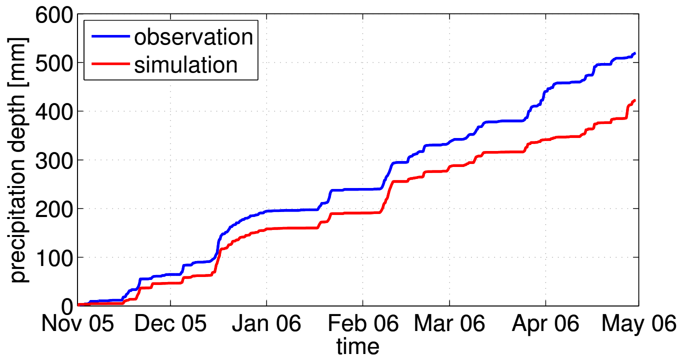

Fig. 4. Comparison of observed and simulated mean areal precipitation depth. The cumulative precipitation depth is derived by calculating the arithmetic mean of 19 stations and 19 corresponding grid points of the limited-area model, respectively.

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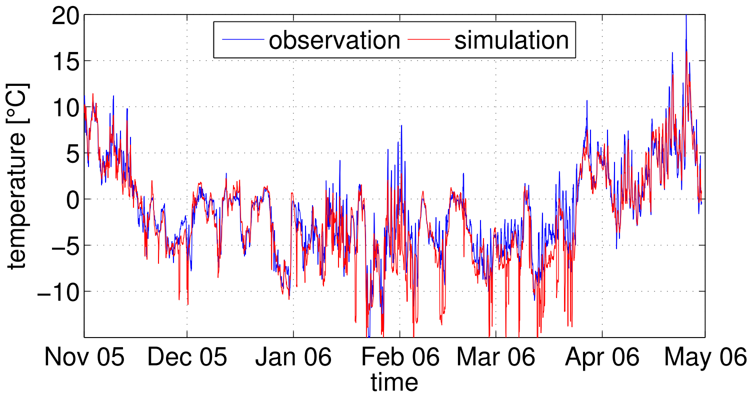

Fig. 5. Comparison of simulated and observed temperature time series at Torfhaus meteorological station. For other meteorological time series, it is referred to Förster (2013).

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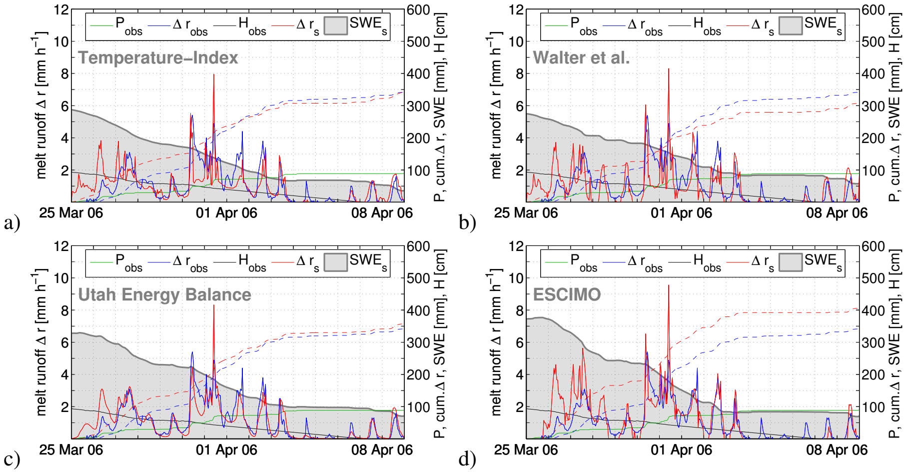

Fig. 6. Snowmelt simulations at the point scale for the winter season 2005/06. Statistics refer to the period 25 March–9 April 2006. **(a)** Temperature-Index approach, **(b)** modified Walter et al. (2005) approach, **(c)** Utah Energy Balance model, and **(d)** ESCIMO. For every simulation run observed precipitation depth (P_{obs}), observed runoff (Δr_{obs}, blue line) including observed runoff depth (blue dashed line), observed snow depth (H_{obs}), simulated runoff (Δr_{s}, red line) including simulated runoff depth (red dashed line), and simulated snow water equivalent ($\mathrm{SWE_s}$) are plotted.

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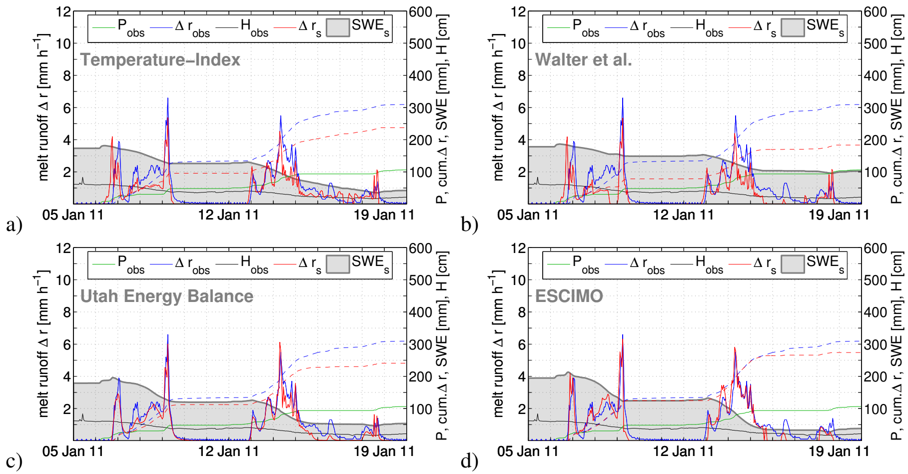

Fig. 7. Snowmelt simulations at the point scale for the winter season 2010/11. Statistics refer to the period 5–20 January 2011. See Fig. 6 for further explanations.

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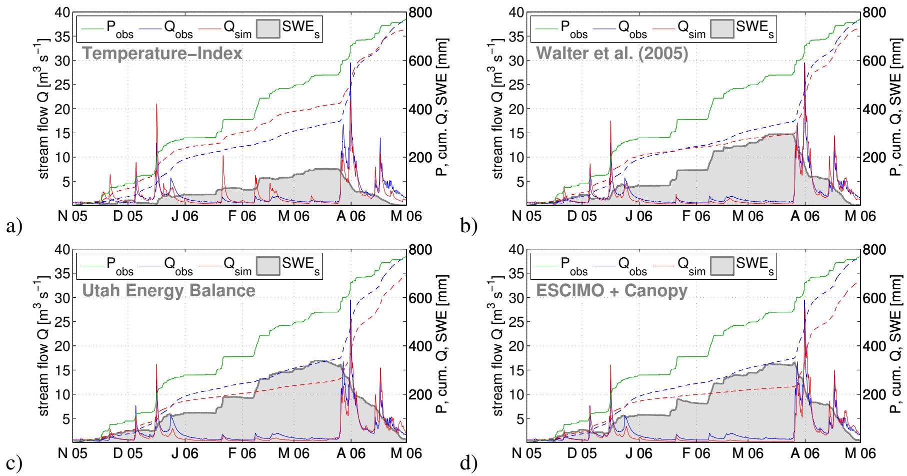

Fig. 8. Snowmelt simulations at the catchment scale for the winter season 2005/06. **(a)** Temperature-Index approach, **(b)** modified Walter et al. (2005) approach, **(c)** Utah Energy Balance model, and **(d)** ESCIMO + Canopy. For every simulation run observed precipitation depth (P_{obs}), observed streamflow (Q_{obs}, blue line) including observed runoff depth (blue dashed line), simulated streamflow (Q_{s}, red line) including simulated runoff depth (red dashed line), and simulated snow water equivalent ($\mathrm{SWE_s}$) are plotted.

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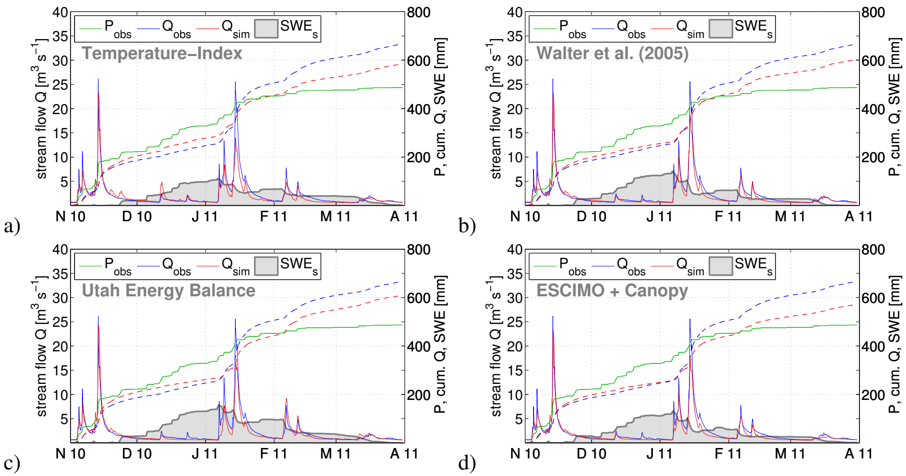

Fig. 9. Snowmelt simulations at the catchment scale for the winter season 2010/11. See Fig. 8 for further explanations.

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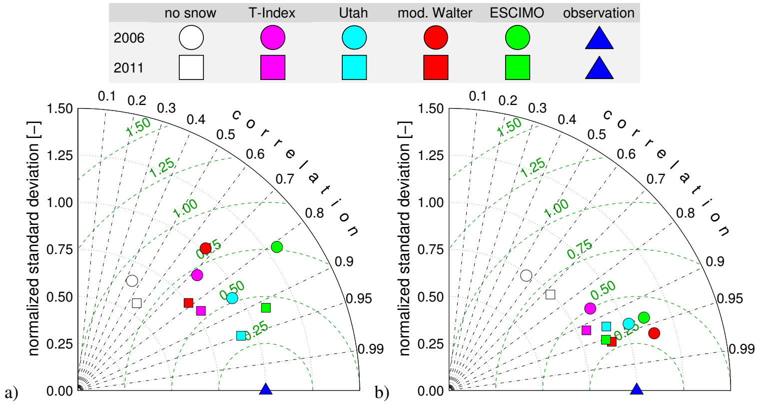

Fig. 10. Taylor diagrams including the results of snowmelt simulations: **(a)** point scale simulations and **(b)** catchment scale simulations.

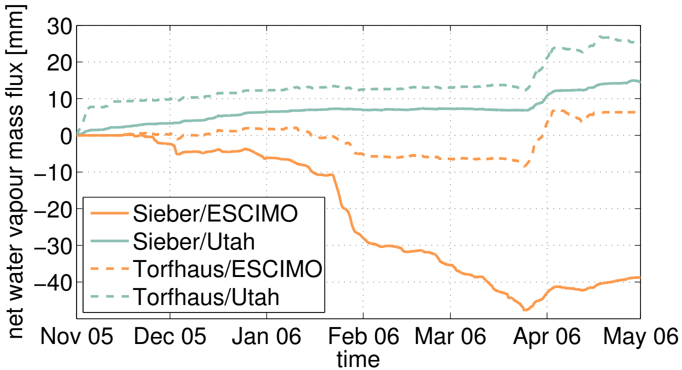

Fig. 11. Simulations of the net water vapour mass flux as calculated by ESCIMO and the Utah Energy Balance Model for the Sieber catchment and Torfhaus meteorological station. Positive values refer to a gain of water vapour due to condensation or resublimation whereas negative values indicate sublimation losses from the snowpack.

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