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The evaluation of the potential of global data products for snow hydrological modelling in ungauged high alpine catchments

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Abstract. Worldwide, there is a strong discrepancy between the importance of high alpine catchments for the water cycle and the availability of meteorological and snow hydrological in situ measurements. Good knowledge on the timing and quantity of snow meltwater is crucial for numerous hydrological applications, also far way downstream. For several decades, the number of global data sets of different meteorological and land surface parameters has been increasing, but their applicability in modelling high alpine regions has been insufficiently investigated so far. We tested such data for a 10-year period with the physically-based Cold Regions Hydrological Model (CRHM). Our study site is the gauged high alpine Research Catchment Zugspitze (RCZ) of 12 km^2 in the European Alps. We used a selection of nine different meteorological driver data setups including data transferred from another alpine station, data from an atmospheric model and hybrid data, whereof we investigated data for all meteorological parameters and substituting precipitation only. For one product, we applied an advanced downscaling approach to test the advantage of such methods. The range between all setups is high at 3.5°C for the mean decadal temperature and at 1510 mm for the mean decadal precipitation sum. The comparison of all model results with measured snow depth and reference simulations driven with in situ meteorological data demonstrates that the setup with the transferred data performs best, followed by the substitution of precipitation only with hybrid data. All other setups were unrealistic or showed plausible results only for some parts of the RCZ. As a second goal, we investigated potential differences in model performance resulting from topographic parameterization according to three globally available digital elevation models (DEMs); two with 30 m and one with 1 km resolution. As reference, we used a 2.5 m resolution DEM. The simulations with all DEM setups performed well at the snow depth measurement sites and on catchment scale, even if they indicate considerable differences. Differences are mainly caused by product specific topography induced differences in solar radiation. Surprisingly, the setup with the coarsest DEM performed best in describing the catchment mean due to averaged out topographic differences. However, this was not the case for a finer resolution. For the two plausible meteorological setups and all DEM setups, we additionally investigated the maximum quantity and the temporal development of the snowpack as well as the runoff regime. Even those quite plausible setups revealed differences of up to 20% in snowpack volume and duration, which consequently lead to considerable shifts in runoff. Overall, we could demonstrate that global data are a valuable source to substitute single missing meteorological variables or topographic information, but the exclusive use of such driver data does not provide sufficiently accurate results for the RCZ. For the future, however, we expect an increasing role of global data in modelling ungauged high alpine basins due to further product improvements, spatial refinements and further steps regarding assimilation with remote sensing data.

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1 Introduction

Worldwide, the vast majority of hydrological catchments can be assumed to be ungauged, which means that within these basins continuous data of in situ measured meteorological and snow hydrological parameters are not available (Abimbola et al., 2017; Blöschl et al., 2013; Hrachowitz et al., 2013). This is critical, as many ungauged basins need deeper information on their hydrological cycle and storages to optimize water usage schemes or hazard management (Merwade et al., 2008; Hirsch and Costa, 2004; Abimbola et al., 2017). However, usually the best available sources of input data for hydrological modelling applications as well as calibration and validation, are in situ meteorological station recordings like air temperature, precipitation, humidity, radiation and wind information as well as recordings at runoff and snow gauges, whereof the latter is particularly important in high alpine areas (Fekete et al., 2015). Due to the large amount of ungauged basins, a lack in such high quality data challenges hydrological modelling, since good quality model output relies on good quality meteorological driver data (Hrachowitz and Weiler, 2011; Gelfan, 2013; Garen, 2013; Massmann, 2019). In particular, a broad range of mountain catchments, which contribute snow melt as major runoff component to the rivers, are affected by the lack of sufficient instrumentation and data (Hrachowitz et al., 2013; Wortmann et al., 2018; Zhang et al., 2015; Dussaillant et al., 2012). This is especially problematic, as mountain catchments are of high relevance for both the local water supply and that of the adjacent lowlands (Bandyopadhyay et al., 1997; Viviroli et al., 2011; Meybeck et al., 2001; Wesemann et al., 2018; Mauser and Prasch, 2015; Zhang et al., 2015; Koch et al., 2011; Huggel et al., 2015).

In this context, the seasonal snow cover in mountains plays a major role for the water cycle (Barnett et al., 2005; Huss et al., 2017; Brown and Mote, 2008). For example, Beniston (2012) shows for the Rhine and the Rhone basins that snow is the biggest single contributor to seasonal runoff. Worldwide, Barnett et al. (2005) estimate that one-sixth of the population lives within snowmelt-dominated catchments and in Asia or North America, the share of meltwater from snow and ice at total runoff is estimated to be more than 30% (Huss et al., 2017). Nonetheless, the instrumentation of high alpine catchments regarding meteorological and snow or runoff measurements is sparse. Reasons for this are manifold, encompassing problems induced due to the complex topography and the remoteness of mountain regions, which makes access and logistics more difficult, labor-intense and expensive. Moreover, further issues could include the lack of funds for installation and maintenance as well as too little or untrained personnel (Sabatini, 2017; Beniston, 2012; Whitfield et al., 2013; Tauro et al., 2018). In particular, snow water equivalent (SWE) measurements, representing the amount of stored water, would be very valuable for hydrological applications. However, they are largely underrepresented in many regions worldwide compared to snow depth measurements, as Haberkorn shows for most European countries. Nevertheless, in situ SWE measurements are increasingly facilitated by continuous improvements of existing methods like snow pillows or scales, which, however, are still likely to struggle with various problems (Johnson and Schaefer, 2002), and developments of new methods like snow sensing with Global Navigation Satellite System (GNSS) signals and cosmic rays (Koch et al., 2019; Schattan et al., 2017).

Besides in situ snow measurements, satellite-based remote sensing serves as a valuable option or additive to derive information on the snow cover and its properties. This is particularly true for snow cover extent products derived with optical sensors despite their major drawback due to cloud coverage (Hall et al., 2002; Gascoin et al., 2019). Contrary, the derivation of snow

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depth or SWE, based on satellite remote sensing products, is still not sufficiently solved, in particular for complex terrain in high alpine environments (Lettenmaier et al., 2015; Bormann et al., 2018). Active microwave products might be, severely affected by relief displacements caused by layover and foreshortening and passive microwave products are too low in their spatial resolution for alpine regions (Vuyovich et al., 2014; Shi and Dozier, 1997, 2000). However, currently the derivation of snow properties via space borne remote sensing is rapidly developing, e.g., by launching new sensors, enhancing the spatial and temporal resolution and the development of new algorithms. Those methods already show promising results in mountainous regions (Rott et al., 2014; Notarnicola, 2020; Lievens et al., 2019). Moreover, numerous promising airborne or combined in situ, airborne and space borne approaches have been developed in the last decades (Currier et al., 2019; Adams et al., 2018; Kim et al., 2018; Bühler et al., 2015), but are still not possible to perform in many mountain areas due to their remoteness and cost issues. Therefore, until now, the snow cover cannot be entirely described solely relying on remote sensing techniques.

All the above mentioned problems, which can lead to the absence of valuable model driver data, especially in ungauged high alpine regions, illustrate that it is a major task for the hydrologic modelling community to develop strategies and to evaluate existing techniques to close this gaps (Klemeš, 1990; Kratzert et al., 2019; Tauro et al., 2018). This was one of the reasons for the International Association of Hydrological Sciences (IAHS) to launch the Prediction in Ungauged Basins (PUB) initiative in 2003 (Pomeroy et al., 2013; Blöschl et al., 2013) in which, many approaches on how to deal with data scarcity and the lack of in situ measured model driver data were gathered, discussed and evaluated. This includes diverse techniques, such as in situ data transferred from other catchments (Liu et al., 2013), using gridded data sets based on remote sensing or atmospheric models as well as using hybrid data that combine in situ measurements, remote sensing and atmospheric modelling (Kahl et al., 2013; Pomeroy et al., 2013). Regarding the latter, two main representatives of hybrid data are reanalysis and land data assimilation products (Poli et al., 2016; Rodell et al., 2004). Both represent a consistent, multi-year description of the atmospheric state. Especially precipitation data is afflicted by errors and needs to be bias corrected, which requires additional effort (Piani et al., 2010; Smiatek et al., 2009; Christensen et al., 2008; Gampe et al., 2019; Muerth et al., 2013) and is difficult to achieve without field measurements (Fatichi et al., 2016; Gampe et al., 2019).

Despite the described shortcomings, globally available atmospheric model, hybrid or remote sensing products are still often the only available meteorological model input data source for ungauged catchments. Moreover, publically available data is a great opportunity for hydrologists with little budget available for data acquisition. This applies to countries with already limited financial resources (Feki et al., 2017; van de Giesen et al., 2014) and affects a large number of remote mountain catchments. Therefore, one goal of our study is to test the potential applicability of different data sources, which can be potentially used as meteorological driver data for snow hydrological modelling in a high alpine region. Regarding globally and publically available meteorological driver data, we test on the one hand data from atmospheric models like the Climate Forecast System Version 2 (CFSV2) and on the other hand, we use hybrid data, such as data of the Global Land Data Assimilation System (GLDAS), ERA-20C and Climate Hazards group Infrared Precipitation with Stations (CHIRPS). There have already been studies in several regions to test such data products (Förster et al., 2016; Fuka et al., 2013; Essou et al., 2016, 2017; Casson et al., 2018), however, as far as we know not solely and explicitly on high-alpine catchments. Some of these studies showed good results, whilst others underlined the importance of adapting the data to regional conditions. In addition, we compare the performance

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of a transfer from data measured at a similar site, which was also suggested as a method for ungauged basins by the PUB initiative (Liu et al., 2013).

Besides meteorological forcing data, land surface information on topographic and land use, is needed for model parameterization. Regarding the latter, differences in land use products have negligible impact on simulations in high alpine areas, which are largely not covered by vegetation. As we only focus on high alpine areas, we neglect potential differences in land use products in this study. This is, however, different for different sources of topographic information. Topographic information is mainly derived from Digital Elevation Models (DEMs) providing information on altitude, aspect and slope angles. This data is crucial since it influences a wide range of model routines such as the calculation of radiation or the transfer of station-recorded temperature to other parts of the catchment. With the generation of DEMs from remote sensing products, these information became globally available since the late 20th century (Farr et al., 2007; USGS, 1996). The largest difference amongst satellite derived DEM products occur due to different viewing angles of the applied sensors and the spatial resolutions of the product. For ungauged basins, topographic information with a high spatial resolution are very rare. For this reason and as a second goal of this study, we additionally investigate possible differences in model performance resulting from different topography parameterizations originating from globally and publically available DEMs with different spatial resolutions and sensing techniques. For this study, we chose exemplarily the three globally available DEMs GTOPO30, ALOS and SRTM to evaluate their effect on the snow hydrological model output.

We conduct our study in the gauged and well-known, high alpine Research Catchment Zugspitze (RCZ) in the European Northern Calcareous Alps (Hürkamp et al., 2019; Härer et al., 2018; Bernhardt et al., 2018). This allows an evaluation with in situ measured meteorological and snow depth data as well as in situ based snow hydrologic reference simulations. The RCZ is largely dominated by a seasonal snow cover, where large parts are covered with snow for more than six months. To simulate the hydrological cycle, we use the physically-based Cold Regions Hydrological Model (CRHM) (Pomeroy et al., 2007), which we already tested intensively with very good results in this area (Weber et al., 2016, 2020). CRHM is discretized in hydrological response units (HRUs) that are defined as "distributed, heterogeneously structured entities having a common climate, land use and underlying pedo-topo-geological associations controlling their hydrological dynamics" (Flügel, 1995). This guarantees a computationally efficient discretization, avoiding overrepresentation of the land surface and optimal representation of its key characteristics. Computational efficiency is particularly important for hydrological simulations in medium to large catchments, and in case, the available budget is too small to access high performance computing. Moreover, CRHM is a good choice as it was already successfully applied in different alpine and arctic cold region catchments including RCZ (Dornes et al., 2008; Ellis et al., 2010; Essery et al., 2009; Fang et al., 2013; López-Moreno et al., 2013; Weber et al., 2020).

We conduct all CRHM model runs for a 10-year period in the past (September 2000 – August 2010), where all input data are available in parallel. The focus of the model output analysis is on the snow cover and runoff. We compare and analyze the results regarding snow depth, snow cover duration, length of the ablation period, maximum SWE, day of the maximum SWE and additionally the catchment runoff. This allows us to assess differences in quantity and temporal development of the simulated snow hydrological situation in the RCZ based on the various meteorological input data sets as well as different DEMs.

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2 The Research Catchment Zugspitze

The high alpine RCZ (center coordinates: UTM 5250416 N 653692 E, Fig. 1) is located in the Zugspitze massif in the European Northern Calcareous Alps and covers an area of 12 km^2. For the peak of Mount Zugspitze (2962 m a.s.l.), Germany's highest mountain, we calculated from the data recorded by the German Weather Service (DWD) an annual mean temperature of -4.5 °C (1981-2010) and an annual precipitation sum of 2080 mm a^{-1} (1981-2010). Due to the geological situation and glacial processes during the Pleistocene and the Little Ice Age (1550-1850), the terrain of the RCZ is characterized by both karst and glacial features, forming a rugged surface (Hüttl, 1999; Hirtlreiter, 1992). Furthermore, the glaciers Nördlicher und Südlicher Schneeferner are located in the catchment, covering a total area of 24.3 ha in 2015 (Hagg, 2020). As the catchment's altitudinal gradient is in total approx. 1600 m, and the surface's heterogeneity in slope angle, aspect and curvature is highly variable, the meteorological and topographic conditions are changing over short distances. The runoff is gauged at 1365 m a.s.l. at the Partnach Spring and shows a clear peak in spring and summer runoff, which is characteristic for the snow-dominated runoff regime. The catchment's upper part (above 2000 m a.s.l.) is free of vegetation, except from sparse alpine meadows and pioneer plants, while areas below 2000 m a.s.l. are characterized by knee wood (Friedmann and Korch, 2010). Despite the predominant permeable karst, tracer studies have shown that the RCZ exclusively drains to the Partnach Spring (Wrobel, 1980; Rappl et al., 2010). This, in combination with the easy accessibility via ropeways and the excellent scientific infrastructure, provided by the Environmental Research Station Schneefernerhaus (UFS), makes the RCZ ideal for (snow-) hydrological research as numerous studies show (Härer et al., 2013, 2018; Hürkamp et al., 2019; Morche and Schmidt, 2012; Weber et al., 2020). Within the catchment, we had access to data from two automatic weather stations (AWS) providing continuous meteorological and snow recordings for at least twenty years (Table 1). Both stations cover all meteorological parameters (Table 1) in an hourly resolution. DWD automatically records the meteorological parameters close to the summit of Mt. Zugspitze, whereas snow depth is measured daily with a snow stake at 2600 m a.s.l. on the Nördlicher Schneeferner. The second station is operated by the Bavarian Avalanche service (LWD) and is located lower at an altitude of 2420 m a.s.l.. The meteorological data from DWD recordings is used as reference model input; the meteorological data from LWD and the snow depth data of both stations serve as validation data for the simulations with different model setups. Due to some huge gaps in the LWD data during summer time, we refrained from using it as model input. However, we use measured SWE at the LWD station, which were available in recent years to determine an under catch of 50% of snow precipitation (Weber et al., 2020). This is well within the range of precipitation underestimation reported in literature (WMO, 2011; Grossi et al., 2017) and is used to correct snow precipitation with a factor of 1.5. Table 1 gives an overview of the RCZ including the locations of the in situ stations and the measured parameters. For more detailed information on the physiography of the RCZ, it is referred to Weber et al. (2016), Friedmann and Korch (2010), Rappl et al. (2010) and Wetzel (2004).

3 Setup of the Cold Regions Hydrological Model

For simulating the water cycle of the RCZ we use CRHM, a physically-based modelling platform, which was explicitly designed to simulate (snow-)hydrological processes in small-to-medium sized catchments in cold arctic and alpine environments

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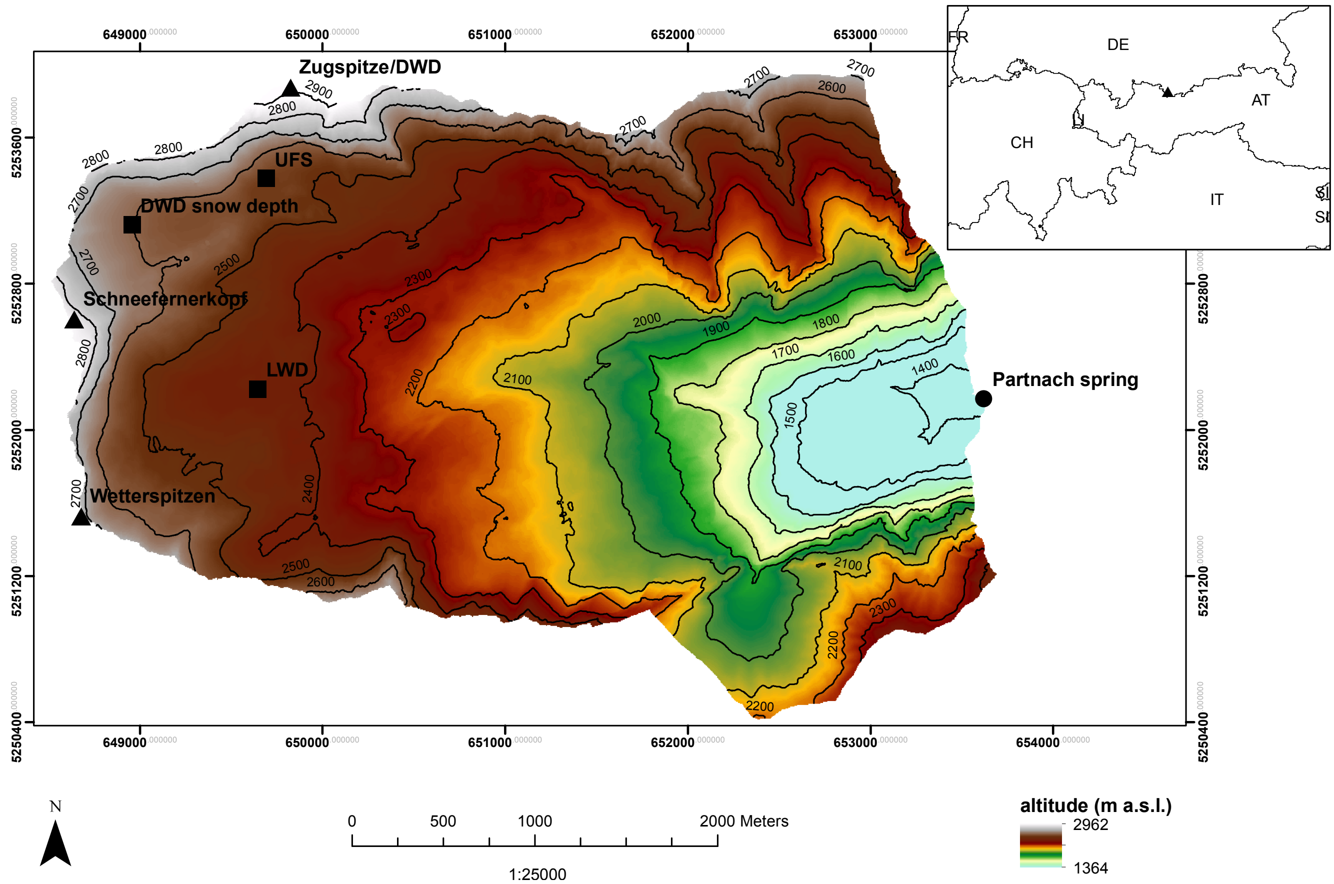

Figure 1. Overview of the Research Catchment Zugspitze (RCZ) and location of in situ stations.

Table 1. Automatic weather stations and measured parameters (T = air temperature, ppt = precipitation, rh = relative humidity, u = windspeed, Qsi = shortwave incoming radiation, Qli = longwave incoming radiation, SD = snow depth).

station name	altitude (m a.s.l.)	measured parameters	data available since
DWD	2964, SD at 2600	T, ppt, rh, u, Qsi, Qli, SD	1900
LWD	2420	T, ppt, rh, u, Qsi, SD	1998

(Pomeroy et al., 2007).

Following the approach proposed by Weber et al. (2020), which is briefly explained in the following, the HRU scheme for RCZ encompasses the same HRUs also for this study (Fig. 2). Weber et al. (2020) derived HRUs via a cluster analysis of the catchment's physiographic properties aspect, slope angle, altitude, vegetation, and a wind sheltering index developed by Winstral et al. (2002). The general idea behind the HRU concept is that one HRU does not necessarily have to be one single

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area, but can contain several areas with similar topographic attributes (Flügel, 1995). To define the appropriate number of clusters, i.e. the appropriate number of HRUs, the cluster analysis needs a reference for evaluation. Since the snow cover is the dominant component of the water cycle of the RCZ, Weber et al. (2020) chose the dominant pattern in the snow cover as reference. This was carried out under the assumptions that snow depth and its distribution are the dominant components in the water cycle of RCZ and that the snow depth distribution is a result of the interaction between meteorology and land surface (Dadic et al., 2010; Mott et al., 2014), i.e. the named physiographic properties. To identify the dominant snow cover pattern, a time series of snow depth maps, which was derived with terrestrial laser scanning was investigated via principle component analysis (PCA). In the following, the clustering that best reflects this PCA derived pattern was chosen as the HRU scheme. For more information on this HRU derivation method, we refer to Weber et al. (2020). The advantage of this approach is that the HRUs are derived objectively and in a sufficient quantity to guarantee optimal representation of the controlling processes while at the same time ensuring computational efficiency. It turned out that ten HRUs are optimal to represent the catchment's snow cover distribution. The areal extension, land cover as well as the main topographic parameters altitude, slope and aspect of these ten HRUs are presented in Figure 2 and for different DEM products in Table 2. The topographic characteristics for the evaluation setup are those of the 2.5 m resolution reference DEM setup.

Regarding the meteorological input, CRHM requires air temperature, relative humidity, precipitation, wind speed, as well as shortwave and longwave incoming radiation for each HRU. CRHM has a modular structure, which allows a model setup according to the available input data and the alignment of the research question. In our setup, melt processes are described by SnobalCRHM (Marks et al., 1999; MacDonald et al., 2010), an energy balance model especially designed for deep alpine snow covers. Aspect and slope angle influence in particular the radiation budget and thus melt processes in the catchment. Therefore, radiation parameters, like direct and diffuse radiation as well as a slope correction are calculated in CRHM with a method created by Garnier and Ohmura (1970) and the net radiation of the whole spectrum is calculated with an approach developed by Brunt (1932). For HRU specific albedo calculations, CRHM uses a procedure developed by Essery and Etchevers (2004) and Pomeroy and Li (2000) created the method to calculate snow transport. Regarding evapotranspiration, CRHM uses an approach developed by Granger and Pomeroy (1997). Interception and sublimation is modelled with a procedure created by Ellis et al. (2010). All these calculations require information on catchment topography, which is characterized by the HRUs (Table 2).

In addition to the necessary information on topography, CRHM needs information on the land cover. In general, the vegetation characteristics of the RCZ are rather simple from a snow hydrological point of view. Only the lower parts are covered with knee wood. This is the reason why we do not apply specific remote sensing data or products to derive further vegetation and land cover data. Instead, we stick to the good description of the land cover of the RCZ by Friedmann and Korch (2010). The extent of the glaciated areas within RCZ is derived from Hagg (2020).

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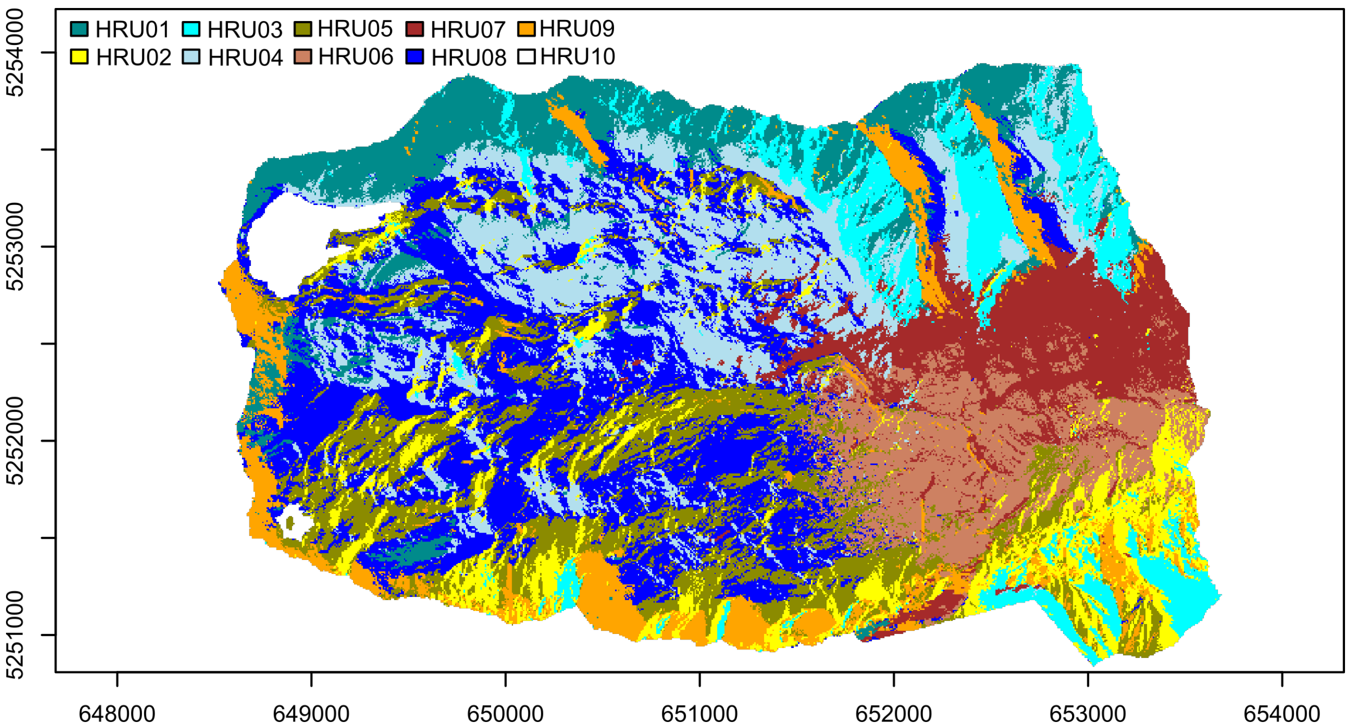

Figure 2. HRU discretization of the RCZ (Weber et al., 2020).

4 Meteorological input data and land surface parameters

4.1 Meteorological input data and their preparation for model input

As meteorological input for the reference simulations, we use the data measured at the DWD station on Mt. Zugspitze, which represents the ‘gauged basin mode’. With these data, we already successfully simulated reliable snow hydrological results, as shown in (Weber et al., 2020). We preprocessed the station measurements at DWD according to Weber et al. (2016). This includes the detection and removal of measurement errors and the interpolation of data gaps according to a procedure proposed by Liston and Elder (2006). The corrected data were then transferred to the HRUs following also the method of Liston and Elder (2006). This method uses monthly variable lapse rates for temperature (Kunkel, 1989) and a monthly variable precipitation adjustment factor (Thornton et al., 1997) for the altitude-dependent adjustment of temperature and precipitation. Relative humidity is adjusted via dew point temperature, which has a relatively linear dependence on elevation (Liston and Elder, 2006). The shortwave incoming radiation (Qsi) is adjusted by a CRHM routine, which uses the ratio of measured Qsi and the calculated clear sky direct and diffuse Qsi on a horizontal plane to adjust the calculated clear sky value on the slope (Garnier and Ohmura, 1970).

To investigate the potential performance of non in situ measured data in the RCZ, we set up the CRHM simulations also for an ‘ungauged basin mode’ with a selection of in total nine different meteorological setups using the following data categories:

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– data from globally available atmospheric models

– hybrid data, which are a combination of satellite products, ground based data and atmospheric models, for all meteorological driver data

– hybrid data using a site-specific downscaling with temperature correction

– hybrid data for the supplementation of precipitation data only

– data transferred from a similar catchment

In order to guarantee for comparability, we chose data that overlaps for at least 10 years, whereof we found the best overlap between September 2000 and August 2010, especially regarding our choice of the hybrid data. Of course, we are aware that there might be several further products available, also several specific local products and for more recent years, but to restrict this study to some major products and categories we came up with the following data sets, which we used as model driver data in 'ungauged-basin mode':

Regarding data from globally available atmospheric models, we forced CRHM with the well-known Climate Forecast System Version 2 (CFSV2) dataset provided by the National Centers for Environmental Prediction (NCEP). CFSV2 is a fully coupled atmosphere-ocean-land model with a resolution of 0.2°(Niu et al., 2011; Saha et al., 2014) and represents an extension to the Climate Forecast System Reanalysis system (Saha et al., 2010).

As hybrid data for the application of all meteorological driver data, we used the following well-known data sources: NASA's Global Land Data Assimilation Systems (GLDAS) (Rodell et al., 2004) and ERA-20C (Poli et al., 2016). GLDAS and ERA-20C products combine in situ measurements, remote sensing and atmospheric modelling. Regarding GLDAS, we use four different versions to test potential differences (Table 3), which all have a temporal resolution of three hours and a spatial resolution of 0.25°. The differences between the GLDAS versions occur in the atmospheric models and the forcing data. Forcing data of GLDAS1 and GLDAS 2.1 simulations are a combination of NCEP's Global Data Assimilation System (GDAS), disaggregated CMAP (CPC Merged Analysis of Precipitation) precipitation (Arkin et al., 2018), and Air Force Weather Agency radiation data sets (Eylander et al.). GLDAS2, is forced with the Princeton Global Meteorological Forcing Dataset (Sheffield et al., 2006) and GLDAS2_repro with an updated version of it. Simulations of GLDAS1 are conducted with the Noah 2.7.1 model (Niu et al., 2011), whereas the other GLDAS simulations are conducted with the Noah 3.3 model. The temporal resolution of the ERA-20C (Poli et al., 2016) data sets is six hours and the spatial resolution is 125 km. Despite the existence of further ECMWF reanalysis products offering a higher spatial resolution, like ERA-Interim with 80 km (Berrisford et al., 2011) or ERA5 with 30 km (Hersbach et al.), we chose ERA-20C. The reason for this is that we additionally wanted to examine the effect of the temperature correction approach by Gao et al. (2012). This approach was developed with ERA-20C data and in situ data from RCZ (ERA-20C_corr). ERA-20C and some GLDAS versions are only available until 2010, while GLDAS2 is continuously available since 2000.

Regarding the category of hybrid products providing precipitation data only, we chose data from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) (Funk et al., 2015; Love et al.), which provides daily precipitation data at a spatial resolution of 0.05°. The idea of choosing CHIRPS data was to test the model performance in case only precipitation needs to be substituted. For the remaining meteorological driver data, we used the measured meteorological reference data. The motivation behind this specific setup was that precipitation gauges are costly to maintain and precipitation measurements in mountain environments are often highly error-prone (WMO, 2011; Grossi et al., 2017; Weber et al., 2020; Germann and Joss, 2004; Hrachowitz and Weiler, 2011), whilst the other input parameters are easier to acquire and more reliable, especially in winter. Thus, there is a frequent interest and need to compensate the lack in precipitation data in high alpine areas.

In addition to the globally and publically available data, we transferred data from another alpine DWD station situated on the top of Mt. Wendelstein (1832 m a.s.l.) (DWD_Wendelstein) to our study catchment. This station is located approximately 84 km in the northeast of RCZ, but is situated in the same alpine climate surrounding at the northern rim of the Alps. We borrowed the recorded data for all meteorological parameters and transferred it to the RCZ following the suggestions from Liu et al. (2013) as presented in the PUB initiative. This station was the best available data set, as we had no access to other alpine data sets in the vicinity at an altitude comparable to the meteorological station at Mt. Zugspitze and for the investigated time period. As no longwave radiation was recorded at Mt. Wendelstein, we used the available cloud cover and temperature data to calculate it following a combination of the approaches from Konzelmann et al. (1994) for clear sky conditions and König-Langlo and Augstein (1994) and Sedlar and Hock (2009) for overcast conditions. Prior to this application, we tested the procedure with measured data from Mt. Zugspitze and could achieve good accordance with a Nash-Sutcliffe-Efficiency (NSE) (Nash and Sutcliffe, 1970) of 0.81. Table 3 provides an overview of all meteorological input data sets used for this study. Additionally, the mean altitude of the datasets is shown – an information that is needed for the transfer of each meteorological parameter to each HRU according to the method by Liston and Elder (2006), which has been described in Section 3. Regarding the station measurements, the listed altitude in Table 3 represents the altitude where the station is located, and for the gridded data, the altitude represents the average altitude of the grid cells covering the RCZ. The average grid altitudes either were provided with the respective data sets or were derived manually from the underlying DEMs of the respective products. Regarding all the globally and publically available data providing the meteorological input, the spatial resolution is coarser than the areal extent of the whole RCZ, which is therefore represented by only one pixel (Table 3). Thus, this data can be considered as a point measurement at the given altitude. Solely the CHIRPS data is slightly finer in its spatial resolution with four pixels covering the entire RCZ. However, the resolution is still too coarse for a precise attribution to the individual HRUs. Therefore, we took the mean of the four pixels as the altitude differences between the four pixels are negligible and treated it like a point measurement.

4.2 Comparison of the different meteorological input data sets

All nine meteorological setups were compared to the meteorological reference data set. Table 4 provides the 10-year mean values of the individual data sets for the RCZ. The range of all meteorological setups in mean decadal temperature is large with 3.5 °C. The mean annual air temperature of the reference is 0.9 °C, which is the warmest value compared to all others. As the CHIRPS setup only supplements precipitation, temperature is of course identical to the reference. With -2.6 °C, the coldest data set regarding the mean annual temperature is represented by ERA-20C. In contrast, the temperature of the ERA-

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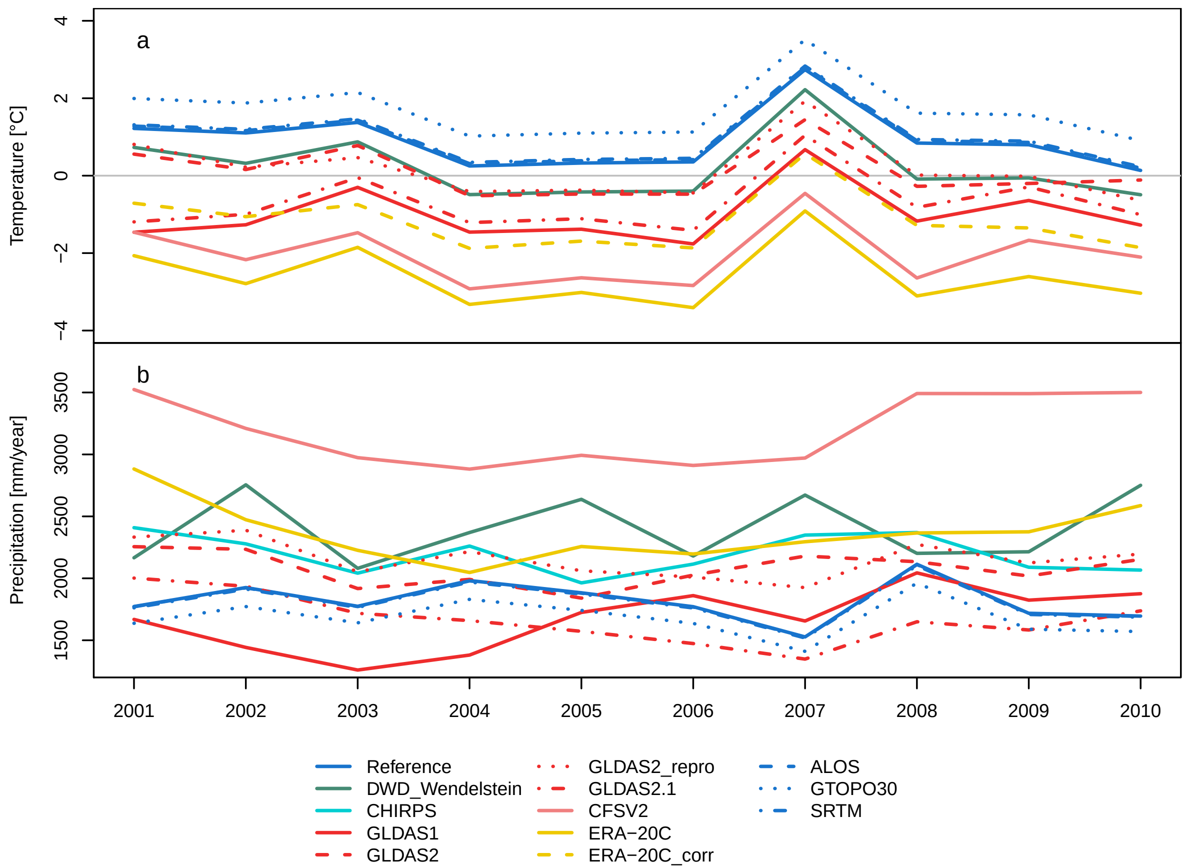

Figure 3. Annual RCZ mean of air temperature (a) and precipitation sum (b) of the input data sets.

20C_corr setup is closer to the reference. The mean annual air temperature of all other driver data is in-between. Interestingly the differences among the GLDAS versions are quite high, which is not only the case for temperature. As Fig. 3a shows, the offsets between all data sets are almost constant over the years.

The range of all meteorological setups in mean decadal annual precipitation sum is with 1510 mm even very high (Table 4). According to the reference data set, the catchment receives a mean annual precipitation sum of 1830 mm. GLDAS1 and GLDAS2.1 are drier with less than 1700 mm a^{-1}. All other data sets indicate wetter conditions. The wettest data set, which has also the highest offset to all other data sets, is CFSV2 with 3161 mm a^{-1} corresponding to 70% higher mean annual precipitation than the in the reference data set. Interestingly, the precipitation measured at the DWD station Wendelstein shows a contrary development to the reference data between 2005 and 2010 (Fig. 3a), which might be due to small scale local effects. The same is true for the GLDAS1 data from 2001 to 2005, while afterwards GLDAS1 precipitation develops in the same way as the reference precipitation and at a similar level. Unlike the air temperature, differences in annual precipitation are much more diverse (Fig. 3b). Besides the annual precipitation sum, an overview on the monthly precipitation sum provides information

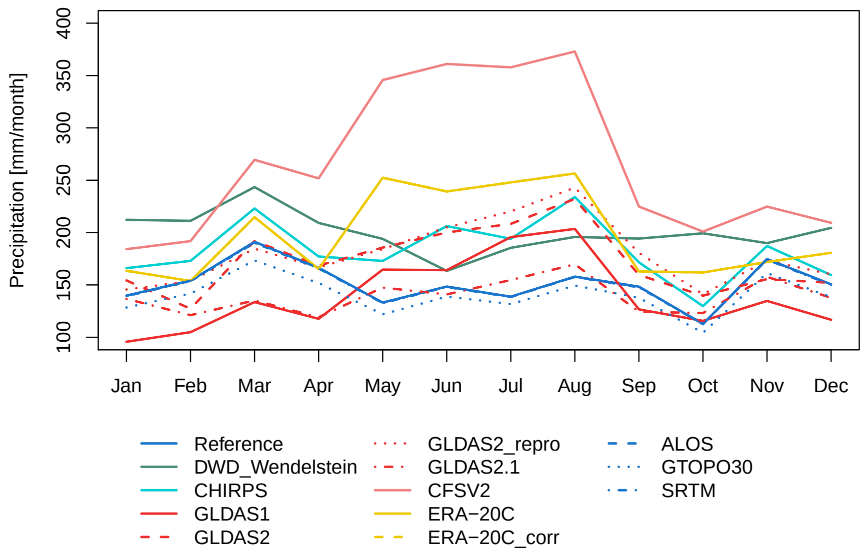

Figure 4. 10-year average of monthly precipitation sums of the input data sets.

on the annual precipitation regime of the individual setups (Fig. 4). In general, the precipitation can be categorized on the one hand into a regime with predominant precipitation during the snow accumulation period which is obvious in the reference and DWD_Wendelstein. On the other hand, it follows a regime with its main precipitation in summer, shown for all other datasets. The reference data shows a clear maximum in March and November which is connected to the snow accumulation season in the RCZ. A similar regime as in the reference can be observed for the dataset of Mt. Wendelstein, however, without the small peak in November. All other meteorological datasets indicate their maximum precipitation in summer. Their small peak in March, however, can be described by a rainfall increase from a local minimum in April to the absolute maximum in August. Within this comparison, the CHIRPS precipitation data set is situated in-between. Its precipitation regime is similar to the reference; however, with a more pronounced maximum in August.

To sum it up, the ERA-20C, ERA-20C_corr and CFSV2 datasets are significantly colder and wetter compared to the reference dataset. The DWD_Wendelstein, GLDAS2 and GLDAS2_repro datasets are slightly colder and wetter, and the GLDAS1 and GLDAS2.1 datasets are colder and drier than the reference. The CHIRPS dataset only differs in precipitation with the reference; however, showing a similar precipitation regime.

4.3 Landsurface parameterization on basis of DEMs

Besides the meteorological input data, land surface information, such as altitude, slope and aspect, are needed to parameterize each HRU (see Section 3). This HRU specific information is needed by CRHM for a number of routines which calculate e.g. albedo, snow transport, the share of snow in precipitation or sublimation (see also Section 3). For the reference setup, we used a 2.5 m resolution DEM derived from an airborne LIDAR flight campaign that was conducted exclusively for the RCZ. However, due to remoteness and high costs, an individual high-resolution DEM data in such a high spatial resolution is not available for the majority of high alpine catchments in the world. Thus, we aim to examine how well land surface information, derived from globally and publically available DEMs, performs for snow hydrological CRHM simulations in the RCZ, where we have the great advantage to compare the results to those derived with the high resolution reference DEM. For this purpose, we exemplarily chose the following three DEMs: the ALOS (Advanced Land Observing Satellite) DEM (Tadono et al., 2014) and the SRTM (Shuttle Radar Topography Mission) DEM (Farr et al., 2007), both with a spatial resolution of 30 m, which makes it interesting to investigate if there are big differences despite the same spatial resolution. Moreover, we chose the GTOPO30 DEM with a spatial resolution of 30 arc seconds (approx. 600 x 900 m in RCZ) (USGS, 1996; Gesch et al., 1999). Especially the SRTM and the GTOPO30 DEMs are well-known and have been frequently used for hydrologic modelling (Ludwig and Schneider, 2006; Nagaveni et al., 2019; Seyler et al., 2009). In 2010, the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) was published to replace GTOPO30. GMTED2010 consists of SRTM data, if available, and of other DEMs with variable resolution outside the SRTM coverage (Danielson and Gesch). However, it is obvious that in more recent years, the DEM products with higher spatial accuracy increased in their usage compared to older and less accurate product like GTOPO30. Nevertheless, we want to examine their performance in snow hydrological modelling since it used to be a standard product for hydrological applications for many years. An additional globally and publically available DEM with a 30 m resolution that was updated in 2019 would be the ASTER DEM (Abrams and Crippen). The parametrized elevation, slope and aspect are well represented by ALOS followed by SRTM compared to the reference SRTM (Table 2). The variance in GTOPO30 regarding slope and aspect angles is very low, which means that almost all HRUs are represented quite similarly. Compared to the reference, for some HRUs parametrized with GTOPO30, the aspect is even almost 180°different, pointing in a totally opposite direction and the slope angles might vary up to 45°, which cannot give a realistic topographic picture of the HRUs. We would like to mention that we only examine the effect of different DEM based parametrizations and not the effect of DEMs on HRU delineation. In case a DEM based HRU delineation method is applied, of course, different HRU schemes than the one applied in this study can be expected.

4.4 Comparison of the different land surface parameterizations and their influence on meteorological conditions

To demonstrate the effect of different topography parameterizations, we chose the reference meteorological data from DWD, adjusted it to the ALOS, SRTM and GTOPO30 HRU parameterizations (Table 2) and compared the different topography-adapted meteorological input data (Fig. 3). Table 4 shows the area weighted 10-year means of temperature and annual precipitation sums. The 0.9 °C higher decadal mean temperature of the GTOPO30 setup compared to the reference DEM setup, is explained by the roughly 100 m lower catchment mean altitude (Table 2), which results from the far lower spatial resolution of this DEM compared to all others. The catchment altitudes of the ALOS and the SRTM setups are 2233 m a.s.l. and 2230 m a.s.l, respectively, which is very close to the one of the reference DEM. Consequently, the DEM-based catchment mean temperature deviates only 0.1 °C from the reference data set. Since the precipitation adjustment is – like the temperature adjustment – also carried out according to an altitude dependent principle (see Section 3), the 10-year mean annual precipitation sum listed in Table 4 shows a similar picture than the 10-year temperature means. In contrast to the ALOS and SRTM setup, the GTOPO30

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setup differs considerably from the reference. Since the original meteorological data corresponds to the meteorological reference data set measured in the catchment and therefore is the same for each DEM setup, the precipitation regime is also the same, with predominant precipitation during the snow accumulation period (Fig. 4). The most pronounced differences among the various HRU parameterizations occur in the mean short-wave incident (Qsi) radiation (Table 4). Since Qsi calculation largely depends on slope and aspect, the differences can be explained by the HRU parameterization shown in Table 2. For a better picture on the Qsi input, Fig. 5 presents the 10-year mean of Qsi in each HRU. The greatest variation in radiation can be seen in the reference setup, and can be explained by the high resolution DEM which better represents small scale differences. As a consequence of the low resolution, the lowest variation can be seen for the GTOPO30 setup. The results of the influence of DEM resolution on radiation input are in line with findings from Hopkinson et al. (2010). For the two DEMs with the same spatial resolution, the variations in the ALOS setup are slightly greater than for the SRTM setup. This is because the SRTM DEM is smoother due to a specific post-processing algorithm used in this product, which is in particular obvious in the steep terrain (Guth, 2006). Here, the ALOS DEM is closer to the reference DEM. Moreover, differences between SRTM and ALOS might also occur due to different sensor viewing angles.

5 Snow hydrological model results

5.1 Evaluation of simulated snow depth with measured data

To evaluate the quality of the snow hydrological results simulated with the input of various meteorological input data as well as different DEMs used for parameterization, we compare in a first step the modelled snow depth with measurements available in the respective HRUs. The DWD snow depth measurement site is located at approx. 2600 m a.s.l. in HRU10, which is one of the highest HRUs in the catchment with its mean reference elevation of 2615 m a.s.l. (Table 2). This site represents perfectly the elevation of the measurement site. The LWD station is located at 2420 m a.s.l. in HRU4 with its HRU mean reference elevation of 2321 m a.s.l. The LWD snow depth measurement is approximately 100 m higher than the HRU mean elevation, and approximately 200 m below the DWD site. The simulation time step is daily; for this reason, we aggregated the measured station data also to daily values.

Figure 6 provides a comparison of the simulated daily snow depth of all different meteorological and DEM model setups including the reference with measured snow depth at the DWD and the LWD stations for the period September 2000 to August 2010. It is obvious that the reference model setup fits best with the measured data for both stations (Fig. 6a, b), which is also reflected in the high statistical values regarding a NSE of 0.79 and R^2 values of 0.81 and 0.86, respectively, as shown in Table 5. At a first glance, it seems that for the reference and the majority of all setups, the simulated results achieved for the LWD station are better captured, although the station is approximately 100 m higher than the mean elevation of HRU4, than for the DWD station. One reason for this could be that the DWD snow depth is measured directly on top of the glacier. The ice has a cooling effect on the snow cover which leads to a delayed melt out of a thin snow cover compared to a faster melt of snow directly on top of rocks. This effect is particularly strong in spring and autumn, and is not considered in the model, which plays,

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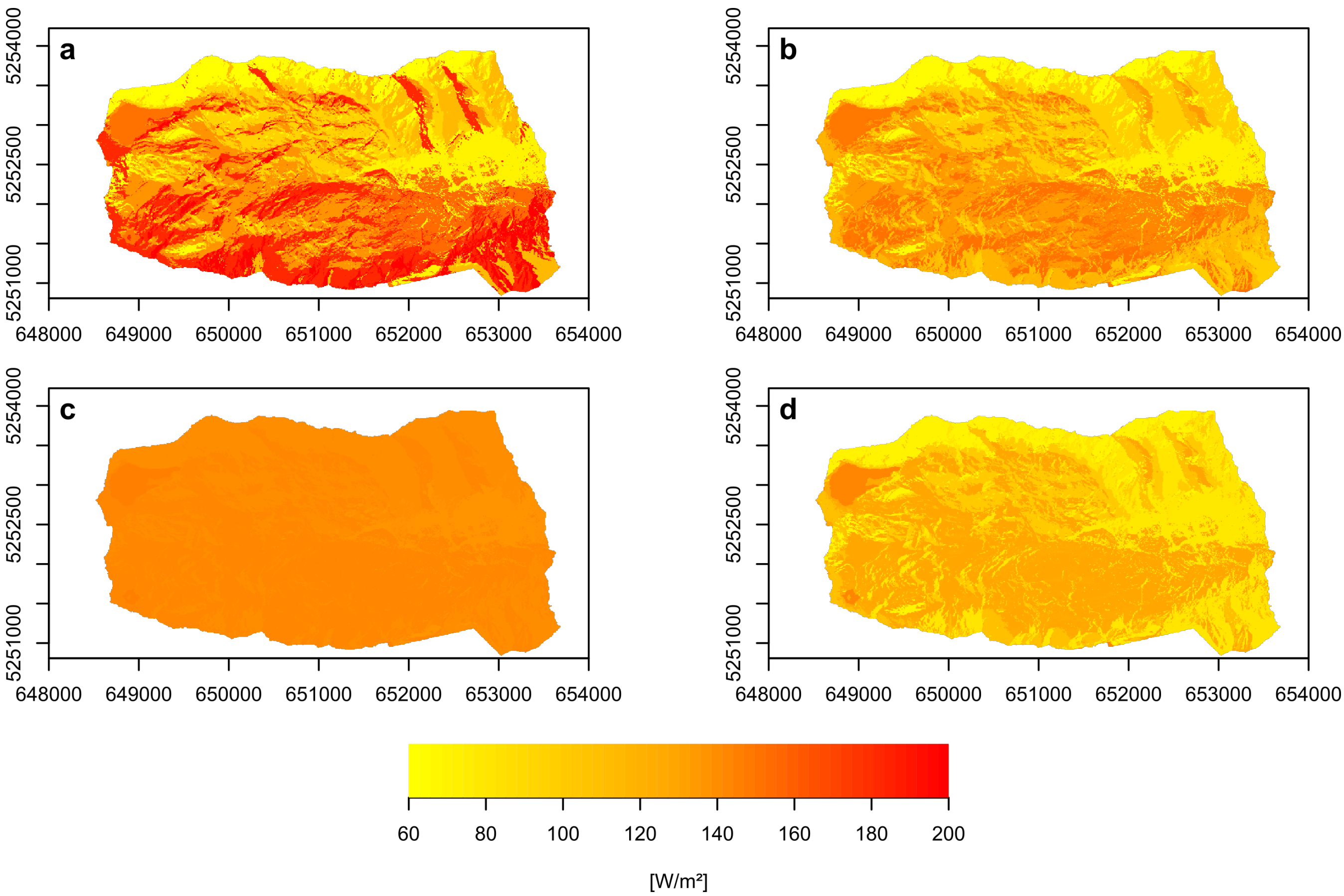

Figure 5. 10-year mean of Qsi in the reference (a), ALOS (b), GTOPO30 (c) and SRTM (d) setup.

however, a negligible role for larger amounts of snow piled on top of the glacier, as it is the case for most of the time during the winter season. Thus, modelled snow cover at the DWD station lasts on average 20 days shorter than the measured one.

The nine setups with different meteorological input data in comparison to the measurements and the reference can be summarized as follows. The simulations, using the transferred data from the DWD AWS Wendelstein (Fig. 6a, b) and the setup with the CHIRPS data, substituting the precipitation input (Fig. 6c, d), produce meaningful results at both measurement stations as the graphs and the quality measures in Table 5 show. After the reference setup, the CHIRPS setup is the best setup regarding all meteorological data sets used for the ‘ungauged basin mode’ in comparison to the measured data with NSE values ranging between 0.54 and 0.55 and R^2 values between 0.66 and 0.79 (Table 5). However, as the CHIRPS precipitation values are higher compared to the precipitation measured directly in the catchment, it indicates also an overestimation of snow depth at the two measurement sites compared to the reference. Further, with the transferred data from the alpine AWS at Mt. Wendelstein we obtained also a good quality with an R^2 of 0.59 and 0.66 at LWD and DWD, respectively. The NSE values at the stations are 0.33 and 0.11, respectively. The comparably high R^2 and the comparably low NSE hint at a good simulation of the temporal

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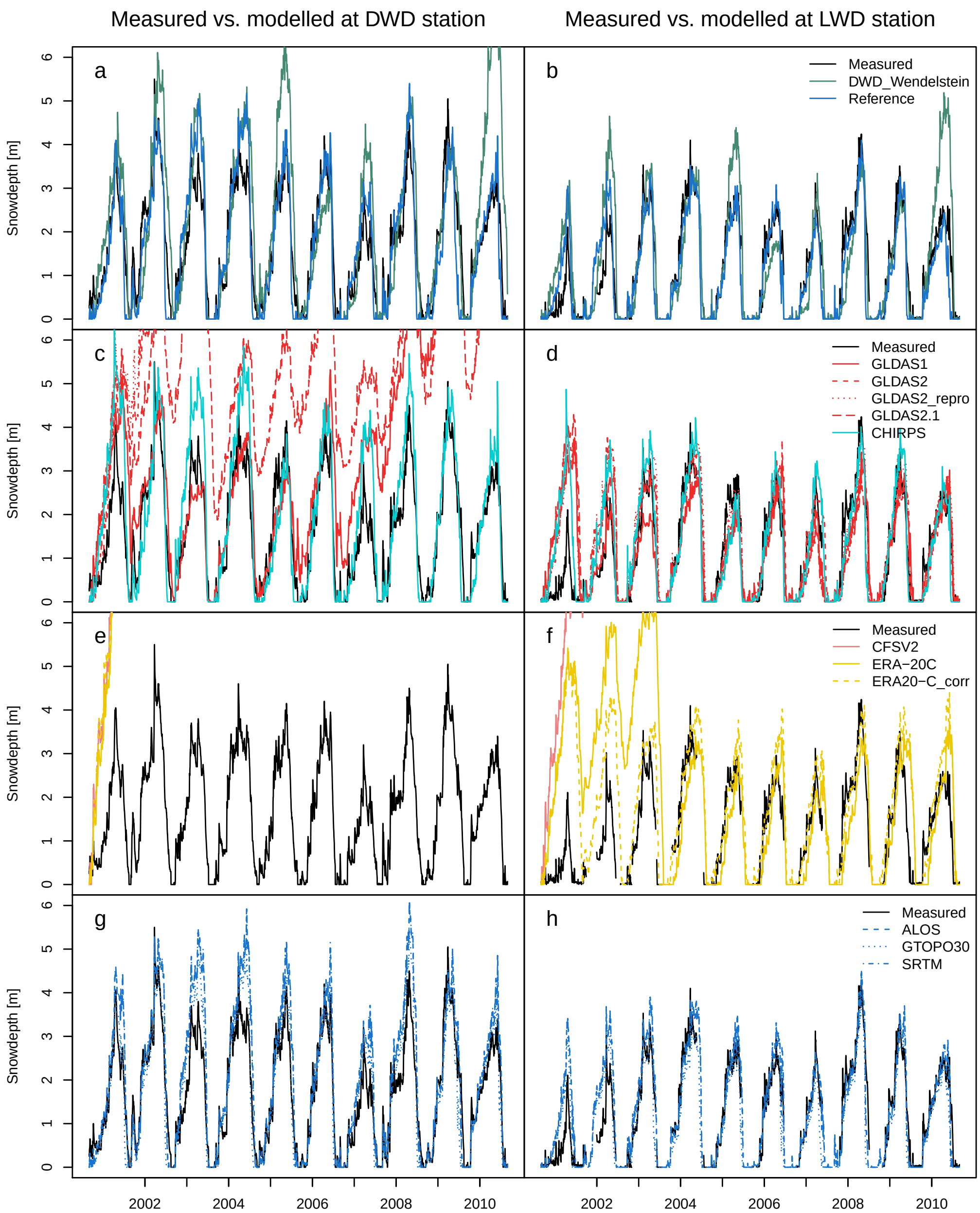

Figure 6. Comparison of modelled snow depth results with measured snow depth at the measurement sites of LWD and DWD. The subplots a to f are related to different meteorological input setups and subplots g and h to different topographic parameterizations using different DEMs.

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development, however, accompanied by offsets. This can be traced back to the fact that the mean decadal temperature of this set up is closest to the reference data set (see Table 4). The snow depth differences occur mainly due to the fact that in some years higher precipitation amounts were measured at Mt. Wendelstein than within the RZC which lead to a snow depth of up to twice as high than in for the reference setup or measured at the stations in some years (Fig. 6a, b). All four GLDAS setups (Fig. 6d) and the ERA-20_corr (Fig. 6f) setup, except for the years 2001 to 2003 that indicate too high snow depths, reflect well the quantity and the temporal dynamics of the snow cover development at the LWD station. However, this is not the case for the simulations at the DWD station (Fig. 6c, e), where so called 'snow towers' pile up resulting in very low R^2 and NSE values; the latter being even largely negative (Table 5). The same can be observed for the CFSV2 setup even at both measurement stations. These simulated snow towers are mainly caused by lower mean annual temperatures and higher amounts of precipitation compared to the meteorological values of the reference data set (Section 4.2). The relatively better performance of the ERA-20C_cor setup compared to the ERA-20C setup originates from the downscaled temperature which has been done by a procedure that was particularly developed for mountain terrain and tested for Mt. Zugspitze (Gao et al., 2012). This is a strong indication that local downscaling of meteorological data in complex terrain is very valuable in order to produce reliable simulation results. Similar conclusions on such corrections are drawn by Buytaert et al. (2010); Teutschbein et al. (2011); Hay and Clark (2003). Moreover, the previously described effect of snow towers also occurs in the two highest located HRUs for all GLDAS and ERA-20C_corr setups and also at further HRUs within the catchment for GLDAS2, GLDAS2.1 and GLDAS2_repro and the ERA-20C data sets (not shown).

In summary, besides the reference setup, only the setups with the transferred data set from the DWD station Wendelstein as well as the simulations with precipitation substituted by CHIRPS give plausible results for all HRUs. When it comes to the substitution of all meteorological parameters as model input using atmospheric model or hybrid or reanalysis data, unfortunately, the validity of the simulation results is largely limited. At least with the GLDAS setups as well as with ERA-20C and ERA20C_corr it was possible to simulate a plausible snow depth for some years and for some HRUs, e.g., at the LWD station. The reason for the lower accordance at the DWD station compared to the LWD station might be that it is located in the highest HRU. This favors temperatures and precipitation amounts which can lead to the development of snow towers. Regarding the model setups with different topographic parameterizations using the three different globally and publically available DEMs ALOS, SRTM and GTOPO30, the offsets in modelled snow depth are less pronounced compared to the results from the setup using the reference DEM. In general, the snow cover development at both measurement sites can be assessed as realistic for all setups (Fig. 6g, h, Table 5). This results in R^2 values above 0.8, and NSE values above 0.77, for all DEM setups at the LWD site. It is remarkable that for GTOPO30, the statistics for the DWD site are even slightly higher. The ALOS and SRTM setups show a slightly lower NSE and R^2 value at the DWD site (Table 5). Besides slight differences in altitude, aspect and slope angles, calculated for the ALOS and SRTM setups, the results are very similar to the reference at the measurement stations (Table 2) which explains their good and quite similar performance. However, as already mentioned for Qsi in Section 4.2, the 30 m DEMs SRTM and ALOS, show also slight differences in the NSE values at both stations.

5.2 Comparison of snow hydrologically relevant parameters

In the following, we present the effect of different meteorological and DEM model input data sets on specific snow cover parameters of the entire RCZ which are of particular interest for hydrological applications, such as water resources management, and are therefore also largely needed information for ungauged high alpine basins. As specific snow cover parameters, we chose the maximum snow water equivalent (MSWE), the day of MSWE (DMSWE), the snow cover duration and the number of ablation days. The latter is defined as the days between the DMSWE and the last day with snow cover. For this investigation, we used the simulated results of the reference setup for comparisons, as SWE measurements were not available for the simulated period. We refrained from evaluating the snow cover parameters DMSWE, the snow cover duration and the number of ablation days with measured snow depth data for two reasons, which occur in particular at the end of the winter season. First, regarding the snow cover duration and the number of ablation days in particular, these parameters cannot be determined in most years at the LWD station with snow depth recordings, because of data gaps due to thunderstruck, which occur mainly in spring and autumn. Second, as already mentioned, the DWD snow depth measurements which are performed directly on the glacier surface might bias the parameters on snow cover duration and ablation periods due to a delayed melt out. Besides the four specific snow cover parameters, we present the effects of the different setups on runoff. We compared the results from different setups also to the simulated reference runoff as an evaluation of modelled with measured runoff data was not possible. One reason for this is the existence of large gaps in the measured runoff data (months to years). Another reason is the generally poor data quality of measured runoff during the analyzed period which is due to maintenance issues in this harsh high alpine environment.

For the analysis of the specific snow cover parameters, we only include the setups, whereof we achieved realistic snow cover developments for each HRU and the entire catchment, which includes, as shown in Section 5.1, the performance at the LWD and DWD stations. Besides the reference setup, this encompasses the simulations with the meteorological data sets DWD_Wendelstein and CHIRPS as well as all three DEM setups.

Investigating the differences caused by the meteorological driver data, Table 6 shows an overestimation of MSWE for the entire RCZ in the CHRIPS and DWD_Wendelstein setup of 15% and 20%, respectively, compared to the reference setup. The higher amounts of MSWE in these two setups are related to the 378 mm higher precipitation in the CHIRPS and 534 mm higher precipitation in the DWD_Wendelstein setup compared to the precipitation measured as reference. Regarding the DWD_Wendelstein setup in combination with the lower mean temperature in this setup, this leads to a 12 days later occurrence of the DMSWE, a 22 days longer snow cover duration and a two weeks longer ablation period in average for the entire catchment. In contrast, the later DMSWE, the longer snow cover duration and the longer melting period modelled with the CHIRPS setup, which are less pronounced than in the DWD_Wendelstein setup, can be attributed to the 15% higher MSWE due to higher winter precipitation. The higher winter precipitation and the consequently higher MSWE in these two meteorological setups, result in a higher runoff of 29 and 30%, respectively (Table 6). However, the runoff regimes presented in Fig. 7 show considerable differences compared to the reference with its peak in June. The peak of the reference setup is in June and occurs in June and July for the CHIRPS setup, whilst the peak runoff of the DWD_Wendelstein setup is even one month later in, which is due to lower spring temperatures that lead to a later occurrence of the main melt period.

Regarding the DEM setups, which were used for the parameterization of the HRUs' slope, aspect and altitude, the mean catchment MSWE reached by the simulation using the GTOPO30 DEM is closest to the simulations with the reference DEM with a deviation of just 1% (Table 6). This good performance goes in line with the comparison of the measured and modelled snow depth data in Section 5.1 (Table 5). Both 30 m resolution DEMs, represent a considerably higher catchment mean MSWE than the reference setup, with the ALOS setup of +18% and the SRTM setup of +17%. In terms of the specific snow cover parameters defining DMSWE and the length of the snow covered and ablation periods, the GTOPO30 setup shows also the smallest deviations compared to the reference setup. The mean catchment DMSWE of the ALOS and SRTM setups occur 11 and 12 days later, respectively, than in the reference setup. Moreover, the snow cover duration in these setups is almost one month longer, which is reflected in their higher number of ablation days, too. Despite the fact that the topography-related air temperatures of the GTOPO30 setup are higher and this setup receives more Qsi than the DEM reference setup, the analyzed snow cover parameters are closest to the reference. The reasons for this are that the air temperature is still low enough during the snow accumulation period that precipitation falls predominantly as snow and that the received Qsi is closest to the reference. In contrast, the considerably less received Qsi in the ALOS and SRTM setup leads to a higher MSWE with a delayed occurrence and longer snow cover durations.

The variations in the modelled snowpack development are also evident in the runoff regime (Fig. 7). The higher MSWE and its delayed occurrence in the ALOS and SRTM setups lead to a shift in peak runoff from June to July compared to the reference and the GTOPO30 setups. Although the snow cover parameters of the GTOPO30 and reference setups are very similar, the GTOPO30 setup exhibits a higher peak runoff and a faster declining recession limb. On the one hand, this can be again explained by the higher received Qsi with less spatial variability (Fig. 5, Table 4) due to the DEM resolution and on the other hand by the lower mean catchment altitude. Both lead to a more homogeneous onset of the melt over the catchment and to its reinforcement.

In addition to the results on the catchment's average, Fig. 8 presents the 10-year mean MSWE, DMSWE, snow cover duration and ablation period for each single HRU, whereof the HRUs are sorted according to their mean altitude (see Table 2). It is obvious that all four parameters increase with altitude in every setup, indicating that altitude is the dominant factor for snow cover development. Most considerable differences for all setups can be observed especially for MSWE. In the different meteorological setups, CHIRPS and DWD_Wendelstein, the differences can mainly be explained with temperature and precipitation, as especially temperature changes are mainly linear with altitude. Differences amongst the DEM-based setups mainly occur due to different Qsi values, which are in turn dependent on slope, aspect and altitude. Regarding Table 2, the slopes calculated for the GTOPO30 setup, never exceed 10°and the aspects ranges only between 100°and 119°representing a quite similar situation for all HRUs. This is however not the case in reality, as demonstrated with the reference setup, which covers slopes up to 50°and a broad range of aspects. The same is true, with only slight losses in variability for the DEM setups ALOS and SRTM, which show for all parameters and HRUs the most similar characteristics. Nonetheless, these two setups show considerable differences in aspect and slope compared to the reference originating from the lower resolution. Compared

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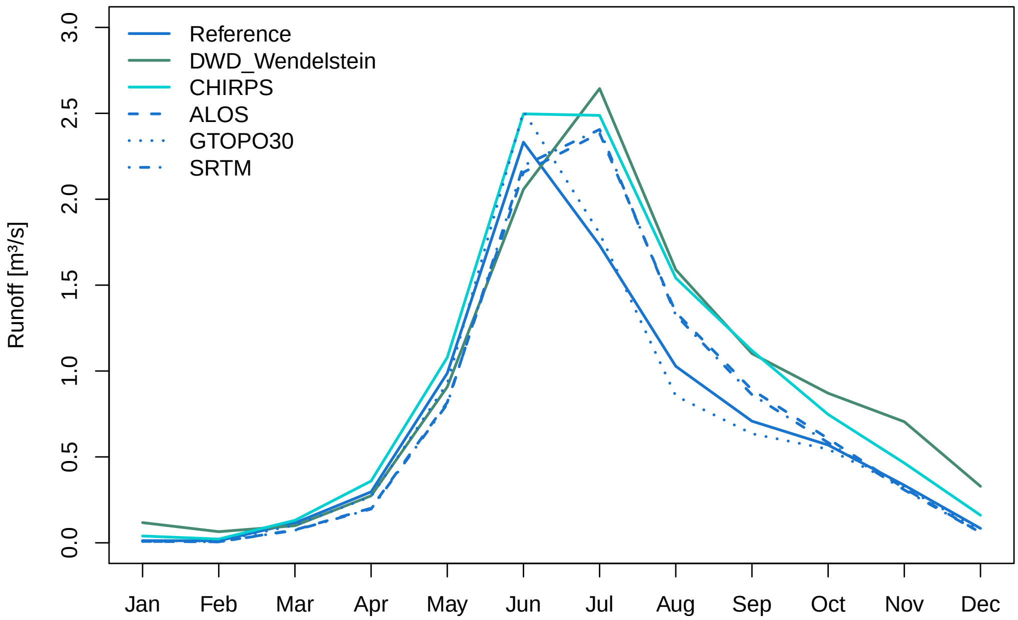

Figure 7. 10-year mean monthly catchment runoff of the RCZ for the five most plausible model setups in comparison to the reference simulations.

to the reference, all snow specific values indicate higher values than for the reference. Despite GTOPO30 is quite similar to the reference setup regarding the results describing the entire catchment, this picture is not true regarding the individual HRUs. The differences between GTOPO30 and all other setups, which are particularly noticeable in HRU1 for MSWE, can mainly be attributed to the product-related up to almost 200 meters lower altitude in HRU1 of this significantly coarser DEM (see Table 2). Moreover, regarding the ablation period, HRU1, HRU6, and HRU10 show considerable differences between the reference and the GTOPO30 setup despite their very similar catchment mean values (see Table 6). The other seven HRUs covering 80% of RCZ, however, are very similar to the results of the other setups, which indicate that this effect is averaged out when looking at catchment means.

6 Discussion on potential applications in ungauged basins

Garen (2013) as wells as Kundzewicz and Stakhiv (2010) state that the usage of remote sensing and atmospheric modelling data is not yet common or even not applicable in hydrological modelling of mountain regions of high spatial variability and steep topographies. Due to the rather low spatial resolution of these data products, their representation of atmospheric parameters is often too coarse to describe complex characteristics like micro-metrological and topographic issues, which play a big role in mountain areas. In this study, we could confirm this statement for all investigated globally and publically available

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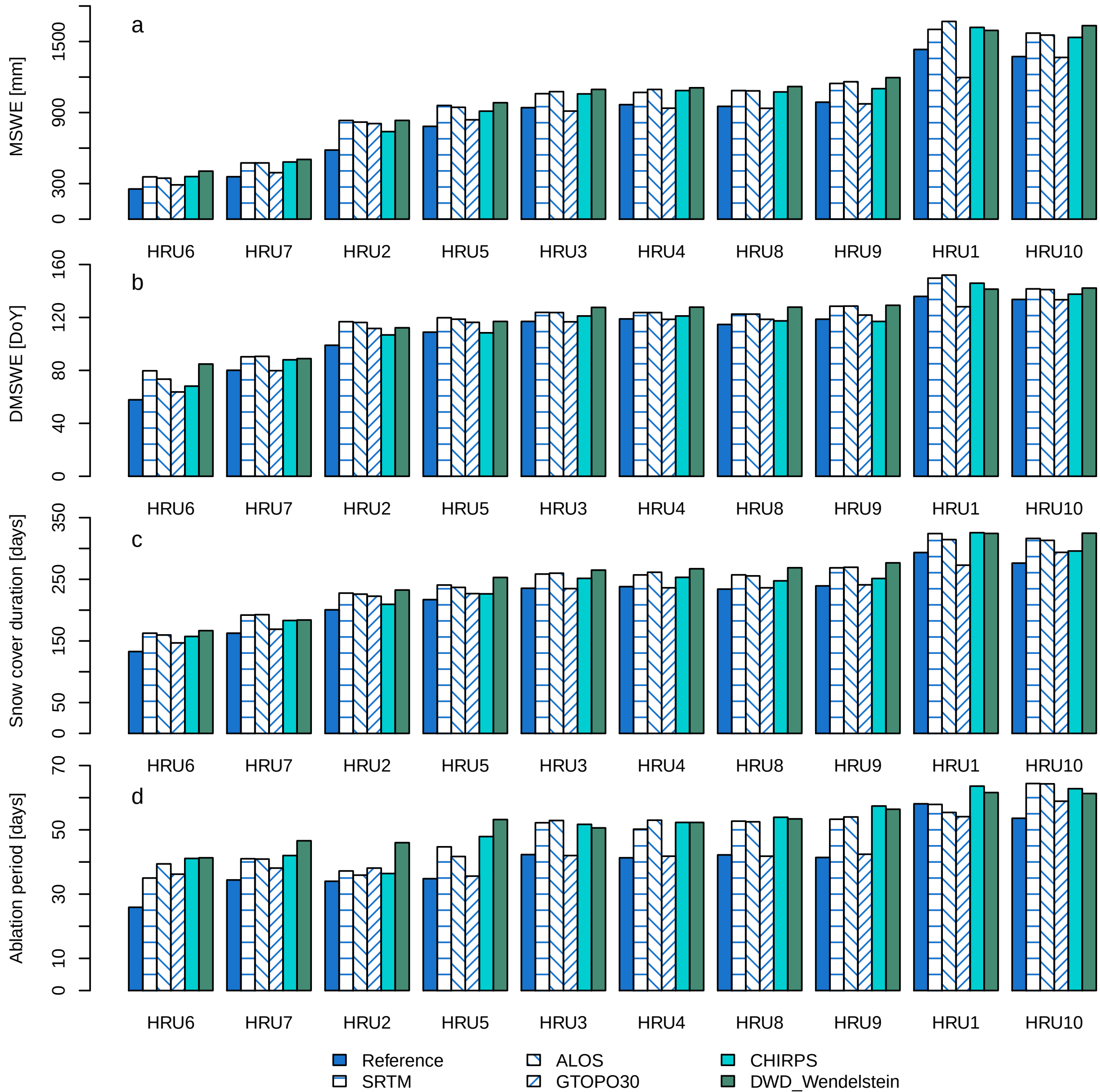

Figure 8. 10-year mean MSWE (a), DMSWE (b), snow cover duration (c), and ablation period (d) simulated for individual HRUs within the RCZ for the five most plausible model setups in comparison to the reference simulations. The HRUs are sorted from the lowest to the highest altitude (see Table 2).

meteorological data sets, from which we used all necessary meteorological parameters as driver data for the simulations. However, the replacement of just one meteorological parameter, in our case precipitation by using the CHIRPS precipitation data set, whilst taking all other meteorological parameters from in situ measurements, produced valid model results for snow cover and runoff. This quite good performance of the CHIRPS data set was also found by Satgé et al. (2019), who used this data set for hydrological modelling of the Lake Titicaca region. The literature findings according to the overall quality of model results using meteorological input data from atmospheric models or hybrid data is not uniform. However, in this regard, it seems to be the case that better results can be achieved for study sites which are not located in mountain regions or which cover only a small proportion of alpine or high alpine areas. In contrast to our study results, for example, Fuka et al. (2013) came to the conclusion that meteorological reanalysis data perform at least as well as measured data at the catchment scale and sometimes even outperform in situ point measurements. Their test sites include a mountain watershed twice as large as RCZ and they tested the Climate Forecast System Reanalysis (CFSR) data, which is the base of CFSV2 (see Section 4.1). Fuka et al. (2013) explain the good model performance with CFSR's ability to well represent the average catchment meteorology in contrast to point measurements. Thus, the weak performance we obtained with CFSV2 hints that this is not valid for the RCZ. In a study from Förster et al. (2016) for the Gepatsch catchment, which is located in the Central European Alps, good results in hydrological modelling could be achieved with CFSV2 driver data. However, they modelled on a monthly basis and used in situ measurements to downscale CFSV2 data in advance – a step which cannot be done for an ungauged basin. Essou et al. (2016) also demonstrates a good performance of reanalysis data as hydrological model drivers including the CFSR and ERA-Interim. Although their study includes mountainous watersheds, the watersheds are much larger than the RCZ and do not include a high alpine headwater catchment. This means that their findings cannot be compared one by one to our high alpine case. In a follow up study including the same watersheds, Essou et al. (2017) propose to use reanalysis data in combination with observation data for regional hydrological modelling to increase performance particularly in snow-dominated catchments. On the other hand, Casson et al. (2018) found that the application of reanalysis data in modelling SWE of subarctic catchments is problematic but can be improved by integrating observed SWE data. In contrast to our study, they used a conceptual model to simulate snow cover development, which could also lead to differences in results compared to the physically-based CRHM we used. The correction of the ERA-20C data set, applying the temperature correction scheme from Gao et al. (2012) increased the quality of this hybrid data set. With this corrected input data, we were able to obtain better descriptions of the snow cover (Fig. 6) at the measurement stations and would recommend applying the scheme to other global data, too. Besides the good results with the hybrid CHIRPS precipitation data set as model input, we also achieved plausible model results for the data set DWD_Wendelstein, by "borrowing" meteorological driver data from another alpine AWS, as suggested by the PUB initiative (Liu et al., 2013). Regarding our results for different meteorological setups, we can conclude that meteorological data transferred from stations in the closer vicinity of less than 100 km distance in the same mountain range and with similar meteorological conditions still provide the best results, when all meteorological input data have to be substituted. Summarized, our analysis shows that the application of unprocessed globally and publically available meteorological data for the usage in small scale modelling of ungauged high alpine headwater catchments hardly produces valid results. This is due to their insufficient representation of small scale, but highly relevant, meteorological variations in steep terrain due to their coarse resolution. This is an effect, which is less pronounced in flat terrain or when averaging over larger areas as the results of Fuka et al. (2013) and Essou et al. (2016, 2017) show. According to Girons Lopez et al. (2020), who investigated the effect of different model structure choices of the HBV model in several catchments in mountainous areas in Central Europe, there may be pronounced differences in the model response on structure changes depending on the catchment. In this context, a potential limitation of our study is that only one high alpine catchment has been tested for all the global meteorological and DEM products. This is because we had no access to such good in situ data like the one we had for the RCZ for other high alpine catchments, which can be used for model evaluation and data validation. Each high alpine catchment has its specific topography and meteorological conditions, which of course have impact on snowpack simulations. Nevertheless, it is likely that the span-width of the results applying the different globally and publically available meteorological and DEM data sets we showed for the RCZ is also large for other high-alpine locations and the results should be similar for high alpine catchments with similar topography in the vicinity. However, the results of this study cannot be transferred one-to-one to other areas.

Regarding the simulation results by using different DEMs, we can make the assumption that no matter which DEM resolution between 2.5 m and up to 1 km is used, the modelled results for the quantity of snow cover and runoff remain plausible. As shown, the differences between the topographic parameterization based on different DEMs are negligible at the two snow depth measurement sites LWD and DWD in the upper parts of the RCZ. This is particularly remarkable for the parameters derived by the GTOPO30 setup, which is in the order of 300 times coarser than the reference and 25 times coarser in resolution than ALOS and SRTM, even if it is not able to describe the topographic conditions for the individual HRUs as shown in Table 2. The almost 100 m lower DEM-dependent average catchment altitude of GTOPO30 plays a minor role, since it is still high enough and temperatures are low enough, respectively that the snow cover like it was measured can develop in the model. Moreover, this suggests that differences among HRUs are averaged out when considering catchment mean values. However, the different DEM setups show more pronounced differences in the simulated snow cover development considering the entire RCZ. This consequently leads to differences in the runoff regime of the RCZ. Those differences can be attributed to the product-dependent radiation budget, which varies due to differences in aspect and slope angle. Although the ALOS and SRTM setups have the same spatial resolution of 30 m, there are considerable differences regarding the steeper parts of the catchment. Here, the SRTM DEM is smoother, probably due to a specific slope algorithm of this product (Guth, 2006), whereas the ALOS DEM resembles more the reference DEM. Moreover, the SRTM DEM has a small area in the lower part of RCZ which shows unrealistically low altitudes which could be caused by unfavorable viewing angles of the radar sensors. These points could easily lead to differences in slope and aspect angles, independent from the spatial resolution of the DEM. In general, we assume that the differences between the tested DEMs are similar also in other high alpine catchments with a similar steep and diverse topography, however, that the differences are less pronounced in smoother alpine terrain like larger mountainous alpine catchments including their forelands.

The presented results show that the meteorological forcing data still is the big problem for snow hydrological modelling in ungauged alpine headwater catchments, whereas the choice of the DEM has far less impact. Therefore, a sound quality assessment of the results is inevitable, when the model is forced with non in situ measured meteorological data. In our study, measured data is available for this task, whereof we could test the potential applicability for ungauged basins. However, this comfortable situation is not the case in most high alpine catchments. In the next decades, model inputs could be completed or assimilated by recently developed or currently being developed high resolution remote sensing products for measuring snow cover properties like snow cover extent, snow depth or even SWE, for such regions with ungauged basins. This includes using unmanned aerial vehicles (Bühler et al., 2015), satellite-based LIDAR (Kwok and Markus, 2018) and aerial LIDAR

(Broxton et al., 2019) for snow depth measurements, high resolution Synthetic Aperture Radar sensors for SWE derivation (Lievens et al., 2019) and satellite-based optical sensors (Notarnicola, 2020; Marti et al., 2016) or webcam data (Härer et al., 2016) for spatially and temporally improved snow cover detection. This could improve the evaluation or initialization of snow hydrological models to deliver data with a sufficiently high spatial resolution. Although the new Sentinel satellite series has a high temporal resolution of up to 2.5 days, however, the 'realistic' temporal resolution especially for optical sensors can be far less due to cloud cover issues. Another point of improvement can be seen for the meteorological reanalysis and land data assimilation methods, as they are also constantly evolved (Hersbach et al.). Products such as SNODAS (Barrett) and products based on it (Lv et al., 2019) indicate a good way in this direction, including ground observations, satellite data and snow hydrological models, which are driven by globally available data to close the temporal and spatial gap between remotely sensed and ground based snow cover data. Considering those developments, we see great potential that snow cover products with high spatial and temporal resolution could be available with large improvements for many alpine headwater catchments in the future.

7 Conclusions

In this study, we examined as a first point, the potential applicability of different globally and publically available meteorological information like data from CFSV2, different versions of GLDAS, CHIRPS, and ERA-20C including a specific downscaling approach, as well as a data transfer from another alpine station to conduct a snow hydrological simulations for a high-alpine basin. As a second point, we tested the impact of DEMs with different spatial resolutions to derive different product-based topography parameterizations for snow hydologic modelling. For the snow hydrological simulations we set up the physically-based CRHM in the well-known and gauged high-alpine RCZ of 12 km^2 in the Northern European Alps for a study period of 10 years (September 2000 – August 2010). In the RCZ we were able to evaluate 'ungauged basin' mode simulations with measured in situ data and reference simulations. Regarding the in total nine different meteorological setups, besides the reference, we could find plausible results for the snow depth development and other snow cover parameters during the winter season at both snow depth measurement sites, for the catchment mean as well as for all HRUs for two setups. This was on the one hand the case by substituting only precipitation data by the hybrid product CHIRPS whilst taking all other meteorological data from the reference in situ data set, and on the other hand, for meteorological data, which was 'borrowed' from another alpine AWS in the catchment's greater vicinity. The globally and publically available data sets substituting all meteorological variables, however, produced for at least some parts of the catchment a totally unrealistic snow cover development, especially at the highest station.To some extent, with the setups based on ERA-20C reanalysis data and different versions of GLDAS, we could simulate the snow cover development at one measurement site quite reasonable. The application of temperature downscaling improved the model quality of the ERA-20C setup. The CFSV2 setup performed worst and produced so called 'snow towers' in all parts of the catchment due to too low temperatures, leading to the fact that the snowpack could not melt completely, even in summer. In contrast, the performance of the setups with different topographic parameterizations based on the GTOPO30, ALOS and SRTM DEMs were more or less comparable to those of the reference setup at the measurement stations – even though they differ widely in their spatial resolution compared to the reference DEM of 2.5 m. As a consequence of their different spatial resolutions between the high resolution of the reference and up to approx. 1 km, differences in altitude, slope and aspect occur, which influences especially the radiation input for simulation. Rather slight differences, however, also occurred in case of comparing the DEMs ALOS and SRTM, which have the same spatial resolution of 30 m due to product specific and viewing angle differences. However, the most pronounced differences are obvious for the GTOPO30 DEM with the lowest resolution, which could not reliably represent the individual HRU topographic characteristics and has therefore the weakest performance regarding the specific snow cover parameters on HRU scale, but nevertheless performs well at catchment scale due to averaging effects. For the best two meteorological and all DEM setups we investigated besides snow depth also the snow hydrologically relevant snow cover properties MSWE, DMSWE, snow cover duration and ablation period as well as the runoff. Similar to the best meteorological setups, the three globally available DEM setups showed considerable differences in catchment averaged modelled snow volume and snow cover duration compared to the reference setup, resulting also in differences in the runoff regime. Whilst for the setups of different meteorological input, the differences of the snow hydrological results can be explained by differences in product-specific temperature and precipitation information, the setups with different topographic parameterization mainly vary due to different mean Qsi values.

Based on our results, we currently cannot recommend the unrestricted use of globally and publically available meteorological driver data substituting all meteorological parameters for snow hydrological modelling applications in high alpine head water catchments for the following reasons. Up to now, the globally available meteorological products are neither able to describe the meteorological heterogeneity of such catchments with steep terrain, nor its average conditions. This is reflected for the RCZ in a range of 3.5 °C in the catchment mean decadal temperature and 1510 mm in the catchment mean decadal annual precipitation sum over all input data in this study. We suggest it could be a similar span-width for globally available meteorological data also in other high-alpine regions and also for other products. This would require specific downscaling or bias correction methods which rely again on measured data (Fatichi et al., 2016; Gampe et al., 2019). Besides, if such data was applied for ungauged basins, the simulated results would still need to be checked for plausibility in the entire modelled region. For such a validation, in situ information on the actual snow cover development would be needed, which is still widely missing in ungauged basins. However, this data might be provided in an increasing manner by remote sensing products in the future. The meteorological products derived from remote sensing and reanalysis in combination with land data assimilation methods are constantly and rapidly developing, including spatial and temporal refinements. Therefore, we are in general optimistic that the role of globally and publically available meteorological data could increase for simulations in ungauged high alpine basins in the future.

Data availability. All global meteorological model input data as well as the global DEM data used for model parameterization are publically available as described in Section 4.1 and 4.3, respectively. The URLs are:

- GLDAS: https://ldas.gsfc.nasa.gov/gldas
- ERA-20C: https://apps.ecmwf.int/datasets
- CHIRPS: https://www.chc.ucsb.edu/data/chirps

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– CFSV2: https://cfs.ncep.noaa.gov
– ALOS: https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm
– GTOPO30 and SRTM: https://www.usgs.gov/centers/eros/science

The meterorological and snow depth station data from the German Weather Service (DWD) is also publically available at https://www.dwd.de. A second set of snow depth station data used for validation was provided by the Bavarian Avalanche Service (LWD) and can be made available upon request and approval by the LWD. The used reference DEM was provided by David Morche (Martin-Luther-University Halle-Wittenberg) and might also be made available upon request and upon approval by the copyright owner.

Author contributions. MW and MB conceptualized the study. MW was responsible for the methodology, carried out the investigations and the formal analysis and wrote the original draft. FK reviewed & edited the manuscript, acquired funds for publication and supervised the work. KS reviewed & edited the manuscript and supervised the work.

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Table 2. Main land cover and topographic parameters of the 10 HRUs of RCZ derived from the reference, ALOS, GTOPO30 and SRTM DEM.

HRU	altitude [m a.s.l.]				aspect [°]				slope [°]				land cover	area [km^2]
	ref	ALOS	GTOPO30	SRTM	ref	ALOS	GTOPO30	SRTM	ref	ALOS	GTOPO30	SRTM		
1	2598	2596	2403	2585	160	163	119	162	44	11	7	39	rock	1.30
2	2104	2104	2109	2102	327	235	118	197	36	33	7	32	rock	0.96
3	2312	2307	2195	2288	243	230	123	214	46	12	6	39	rock	0.97
4	2321	2320	2215	2320	175	163	116	160	24	23	7	23	rock	1.81
5	2228	2227	2137	2230	29	83	112	114	22	21	7	23	rock	0.71
6	1687	1683	1591	1690	81	94	108	110	26	25	6	26	knee wood	1.03
7	1803	1802	1737	1806	155	153	118	151	40	39	10	37	knee wood	1.11
8	2329	2328	2213	2327	102	109	113	117	19	19	8	20	rock	2.71
9	2376	2375	2246	2360	59	109	117	118	51	45	6	40	rock	0.90
10	2615	2610	2506	2631	81	88	100	98	14	14	5	16	ice	0.23

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Table 3. Used meteorological data sets (T = temperature, rh = relative humidity, ppt = precipitation, Qsi = shortwave incoming radiation, Qli = longwave incoming radiation, u = wind speed, AWS = automatic weather station).

data set	temporal resolution	type	spatial resolution	altitude [m a.s.l.]	parameters
reference	h	AWS	point measurement	2964	T, rh, ppt, Qsi, Qli, u
DWD_Wendelstein	h	AWS	point measurement	1832	T, rh, ppt, Qsi, cloud cover, u
GLDAS1	3h	hybrid	0.25°	1530	T, rh, ppt, Qsi, Qli, u
GLDAS2	3h	hybrid	0.25°	1530	T, rh, ppt, Qsi, Qli, u
GLDAS2_repro	3h	hybrid	0.25°	1530	T, rh, ppt, Qsi, Qli, u
GLDAS2.1	3h	hybrid	0.25°	1530	T, rh, ppt, Qsi, Qli, u
ERA-20C	6h	hybrid	125km	1287	T, rh, ppt, Qsi, Qli, u
ERA-20C_corr	6h	hybrid	125km	1287	T, rh, ppt, Qsi, Qli, u
CFSV2	6h	simulation	0.20°	1540	T, rh, ppt, Qsi, Qli, u
CHIRPS	d	hybrid	0.05°	1909	ppt

Table 4. 10-year RCZ mean of annual air temperature and annual precipitation sum of the input data sets. Area weighted 10-year catchment mean of temperature, annual precipitation sum and shortwave incoming radiation (Qsi) of the reference setup and the setups global meteorological data and land surface paremterization on basis of global DEMs.

data set	temperature mean [°C]	precipitation [mm a^{-1}]	Qsi [W m^{-2}]
reference	0.9	1830	139
DWD_Wendelstein	0.2	2364	139
GLDAS1	-1.0	1651	139
GLDAS2	0.1	2066	139
GLDAS2_repro	0.2	2154	139
GLDAS2.1	-0.7	1660	139
ERA-20C	-2.6	2347	139
ERA-20C_corr	-1.2	2347	139
CFSV2	-2.0	3161	139
CHIRPS	0.9	2208	139
GTOPO30	1.8	1691	147
ALOS	1.0	1814	124
SRTM	1.0	1809	116

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Table 5. Statistical overview of simulation results of snow depth by using different meteorological input data and topography parameterizations according to different DEMs and measurements performed at the measurement sites of DWD and LWD.

data set	NSE LWD	NSE DWD	R^2 LWD	R^2 DWD
reference	0.79	0.79	0.81	0.86
DWD_Wendelstein	0.33	0.11	0.59	0.66
GLDAS1	0.46	-6.25	0.49	0.12
GLDAS2	0.31	-195.84	0.47	0.01
GLDAS2_repro	0.36	-266.87	0.55	0.01
GLDAS2.1	0.14	-8.11	0.33	0.39
ERA-20C	-2.57	-743.77	0.09	0.00
ERA-20C_corr	-0.55	-690.06	0.37	0.00
CFSV2	-25.53	-37.22	0.07	0.00
CHIRPS	0.55	0.54	0.66	0.79
GTOPO30	0.79	0.84	0.81	0.89
ALOS	0.77	0.68	0.83	0.89
SRTM	0.79	0.66	0.83	0.89

Table 6. Catchment 10-year means of MSWE, DMSWE, snow cover duration, ablation days and runoff in RCZ.

data set	MSWE [mm]	DMSWE [DoY]	snow cover duration [days]	ablation days	runoff [$m^3 s^{-1}$]
reference	854	108	223	40	0.69
DWD_Wendelstein	1028 (+20%)	120	255	54	0.90
CHRIPS	984 (+15%)	113	239	52	0.89
GTOPO30	849 (-1%)	111	226	42	0.67
ALOS	1007 (+18%)	119	247	50	0.74
SRTM	999 (+17%)	120	248	51	0.74