

## Special Section: Hydrological Observatories

### Core Ideas

- Pre-alpine areas face more intense warming and extreme hydrological events than the global average.
- Climate and land management change have far-reaching impacts on ecosystem functions and services.
- We have improved knowledge of water, energy, and matter exchange by long-term observations and modeling.

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# The TERENO Pre-Alpine Observatory: Integrating Meteorological, Hydrological, and Biogeochemical Measurements and Modeling

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Global change has triggered several transformations, such as alterations in climate, land productivity, water resources, and atmospheric chemistry, with far reaching impacts on ecosystem functions and services. Finding solutions to climate and land cover change-driven impacts on our terrestrial environment is one of the most important scientific challenges of the 21st century, with far-reaching interlinkages to the socio-economy. The setup of the German Terrestrial Environmental Observatories (TERENO) Pre-Alpine Observatory was motivated by the fact that mountain areas, such as the pre-alpine region in southern Germany, have been exposed to more intense warming compared with the global average trend and to higher frequencies of extreme hydrological events, such as droughts and intense rainfall. Scientific research questions in the TERENO Pre-Alpine Observatory focus on improved process understanding and closing of combined energy, water, C, and N cycles at site to regional scales. The main long-term objectives of the TERENO Pre-Alpine Observatory include the characterization and quantification of climate change and land cover-management effects on terrestrial hydrology and biogeochemical processes at site and regional scales by joint measuring and modeling approaches. Here we present a detailed climatic and biogeophysical characterization of the TERENO Pre-Alpine Observatory and a summary of novel scientific findings from observations and projects. Finally, we reflect on future directions of climate impact research in this particularly vulnerable region of Germany.

Abbreviations: CML, commercial microwave link; EC, eddy covariance; GHG, greenhouse gas; ICOS, EU Integrated Carbon Observation System; IMK-IFU, Campus Alpin, Institute of Meteorology and Climate Research; KIT, Karlsruhe Institute of Technology; MAP, mean annual precipitation; MAT, mean annual air temperature; TERENO, German Terrestrial Environmental Observatories; UAV, unmanned aerial vehicle.

Finding solutions to the impacts that global change (i.e., climate and land cover change) exerts on our terrestrial environment is one of the most important challenges of the 21st century. Global change has triggered several transformations, such as alterations in climate, land productivity, water resources, and atmospheric chemistry, with far-reaching impacts on ecosystem functions and services. These changes are diverse and interlinked, exhibit complex feedback mechanisms, and occur at various spatial and temporal scales. To address these formidable challenges for environmental research, improved process understanding of water, energy, and matter exchange and the development of mitigation and adaptation strategies are required. Hence, the setup of integrated, multi-compartment (atmosphere, pedosphere, hydrosphere) measuring infrastructure for environmental monitoring and research has evolved during the last decades (Zacharias et al., 2011). Among others, the US National Ecological Observatory Network, the EU Integrated Carbon Observation System (ICOS), the Chinese Ecosystem Research Network, or the German Terrestrial Environmental Observatories (TERENO) aim to observe and document the long-term ecological, social,

and economic impact of global change at site to regional scales. With four observatories across Germany, TERENO spans a terrestrial observation network that extends from the North German lowlands to the Bavarian Alps. TERENO is embarking on new paths using a harmonized, interdisciplinary, and long-term research program, linking observations with process-based modeling and scale integration. TERENO Pre-Alpine is the southernmost of the four TERENO observatories. It is operated by the Karlsruhe Institute of Technology (KIT) at its Campus Alpin, Institute of Meteorology and Climate Research (IMK-IFU), Garmisch-Partenkirchen (Germany). It comprises various measuring sites, mainly located in the Ammer and Rott catchments, in the pre-alpine region of South Germany. In general, TERENO observatories are an open research platform intended to foster new collaborations and extend existing ones nationally and internationally. The TERENO Pre-Alpine Observatory integrates meteorological, hydrological, and biogeochemical measurements and activities from the atmospheric boundary layer through the atmosphere-ecosystem interface down to the aquifer. In brief, interdisciplinary research in the TERENO Pre-Alpine Observatory spans the variability and interaction of interlinked water, energy and nutrient cycles, including ecosystem C and N dynamics, and associated exchange processes with the atmosphere (greenhouse gases [GHGs]) and hydrosphere (N leaching). Thus, it also links to the global network of Critical Zone Observatories, aiming for the holistic interdisciplinary study of the near-surface terrestrial environment across wide spatial and temporal scales (Lin et al., 2011). The TERENO Pre-Alpine Observatory is regionally well integrated because it complements networks of the German Weather Service and the Bavarian Environmental Agency. TERENO pre-alpine research is conducted in close cooperation with farmers and other stakeholders who are interested in climate-adapted management strategies.

We first present the overall motivation for setting up the TERENO Pre-Alpine Observatory and related meteorological, hydrological, and biogeochemical key objectives. We provide a detailed biophysical characterization of the observatory and an overview of the measuring infrastructure, with data collected since 2009 at several sites along an elevation gradient from 595 to 1684 m asl, with annual precipitation ranging from 959 to 1717 mm. We highlight the use of advanced methods such as rainfall observation with commercial microwave link networks. Based on long-term observations and dedicated campaigns, we present examples of novel scientific findings from published research and practical implications (e.g., for national fertilizer use regulations). Finally, we reflect on future perspectives of combined meteorological, hydrological, and biogeochemical investigations (measurements and modeling) and intended new directions of research in the TERENO Pre-Alpine Observatory.

## Motivation and Science Questions

The TERENO Pre-Alpine Observatory covers parts of the Bavarian Alps (Ammergau Mountains) and their foreland, with

the Ammer and Rott catchment (655 km<sup>2</sup>) areas at its core (Fig. 1). The setup of the observatory in this region was motivated by the fact that such mountain areas have been exposed to more intense warming compared with the global average trend and to higher frequencies of extreme hydrological events, such as droughts and intensive rainfall (Böhm et al., 2001; Calanca, 2007). Analyses of the temperature time series for the Mount Hohenpeissenberg German Weather Service station reveal a mean temperature increase of 1.5°C for the years 1880 to 2012. This corresponds to around twice the globally averaged combined land and ocean surface temperature increase of 0.78°C and clearly exceeds the average global land temperature increase of 1.17°C for the same period (<https://www.ncdc.noaa.gov/>). Mountain areas are characterized by steep topographically induced climate gradients, enabling study designs spanning different climatic zones along short distances. In the Ammer catchment region of the observatory, temperature lapse rates are around 0.6°C per 100 m in summer and 0.45°C per 100 m in winter (Kunstmann et al., 2004). For the region covered by the observatory, Kunstmann et al. (2004) anticipate an increase of mean annual temperatures between 3 and 4°C and a rise of mean annual precipitation (MAP) by around 20% based on climate change projections resulting from two ECHAM4 (global circulation model) time slices: 2031/2039 and 1991/1999, dynamically downscaled with MM5 (regional mesoscale model) to 4 km spatial resolution. These very early, convection-permitting, high-resolution, regional climate simulations indicated significantly different responses in the climate change signal over small distances, with clear differences across major valleys and ridges. A subsequent hydrological climate change impact analysis with the distributed hydrological model WaSIM showed decreased summer but enhanced winter runoff for the Ammer catchment (Kunstmann et al., 2004).

The region was also selected as one out of three German target regions for a concerted high-resolution regional climate change analysis where two regional climate models, CLM and Weather Research and Forecasting, were used for downscaling two 30-yr time slices of the IPCC special report of emission scenarios A1b scenario to 7 km spatial resolution (Ott et al., 2013). It was shown that most of the uncertainty of the change signal arises from the natural variability in winter and from the regional climate model spreads in summer.

The dominant land cover types of the observatory are forests (44%) and grasslands (38%). Croplands (7%), water surfaces and wetlands (6%), settlements (4%), and unvegetated areas (i.e., rocks) (1%) are of minor importance (Fig. 2a). Because grassland is the dominant land cover particularly in the valley bottoms, most of the individual measuring sites operated in the TERENO Pre-Alpine Observatory are established mainly on grassland sites. Similar to even larger areas in Austria, Italy, France, Switzerland, and other mountainous regions of the world, these alpine and pre-alpine sites are mainly used for fodder production and thus provide important economic value through milk and meat production (Soussana and Lüscher, 2007). However, grassland cultivations are not only

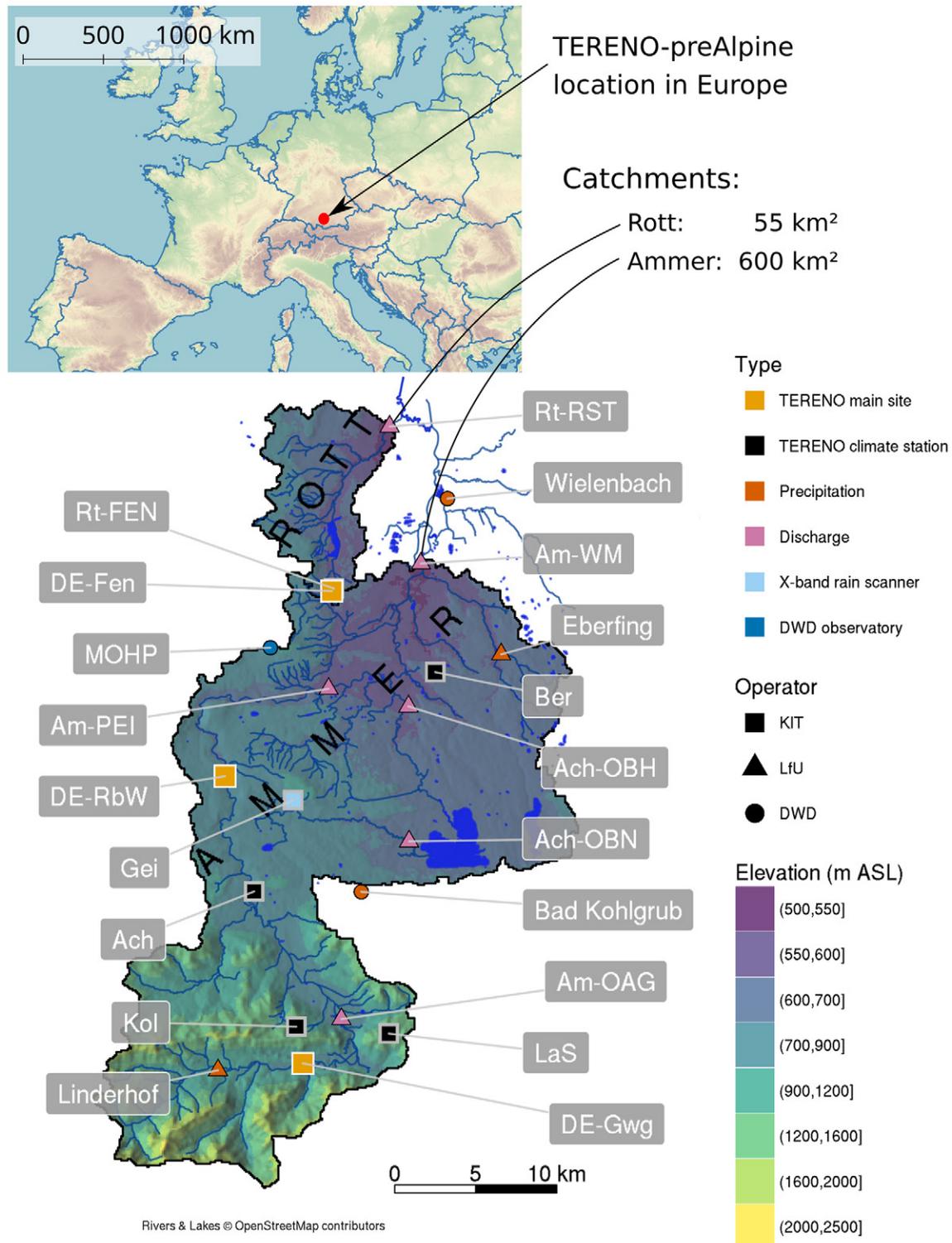


Fig. 1. Overview of the TERENO Pre-Alpine Observatory outline and the measurement site locations within the Ammer (Am) and Rott (Rt) river catchments. Operators are Campus Alpin of Karlsruhe Institute of Technology (KIT), Bavarian Environmental Agency, and German Weather Service. Station IDs are detailed in Supplemental Tables S1 and S2.

of eminent importance economically; they also provide various ecosystem services that regulate, support, and underpin the environment we live in. These environmental services include the function of soils for (i) C and N storage, with feedback to climate

change, soil fertility, and biodiversity; (ii) water retention; and (iii) recreation and tourism (Chan et al., 2006; Kremen, 2005). Climate change can impose severe threats to the aforementioned functions and will require agricultural adaptations to further

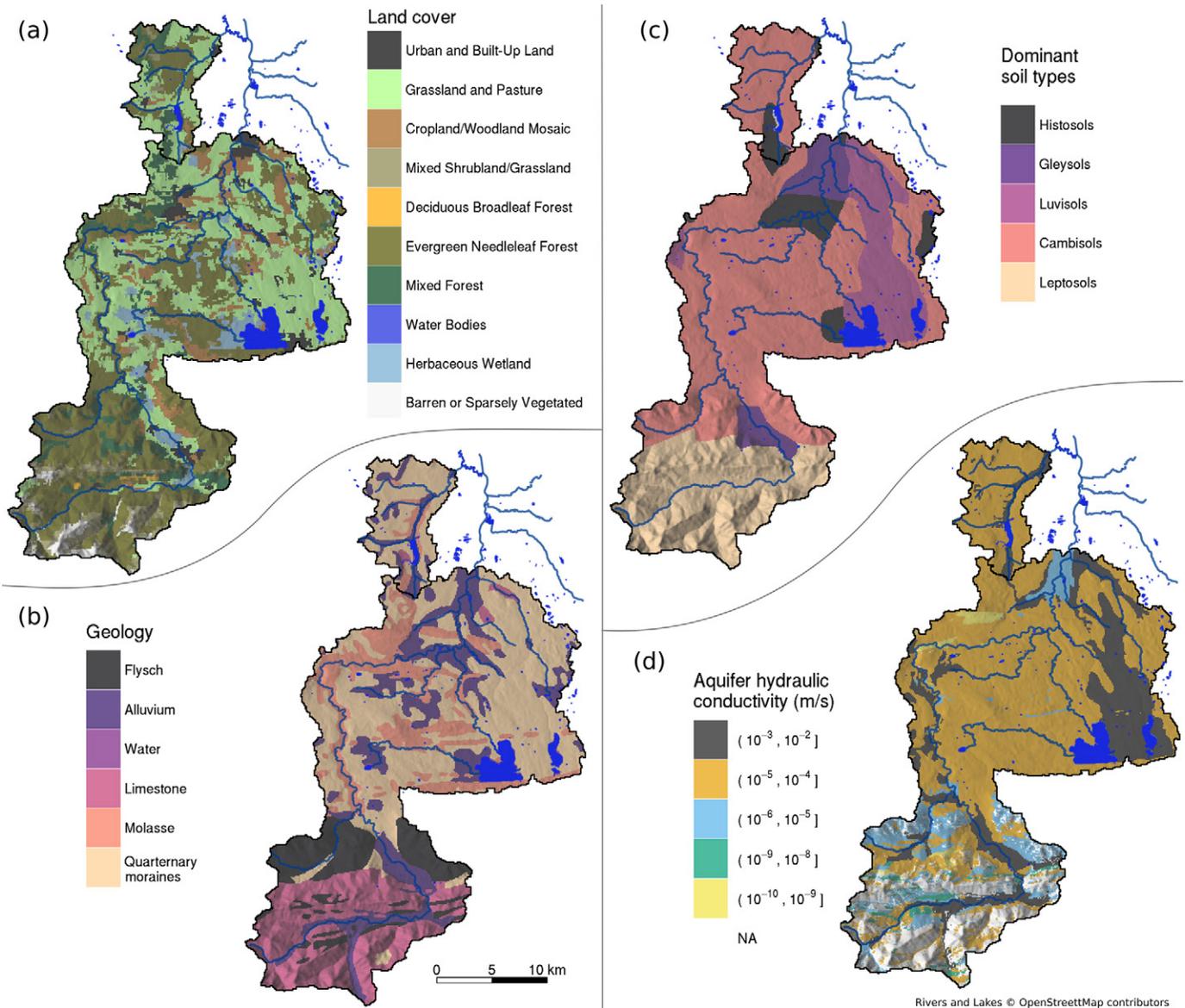


Fig. 2. (a) Land cover (source: EU CORINE land cover, reclassified to USGS scheme), (b) geology (source: Bavarian Environmental Agency, geological map 1:500,000, GK500), (c) dominant soil types (source: Bundesanstalt für Geowissenschaften und Rohstoffe [BGR], soil map of Germany 1:1,000,000, BÜK 1000, denoted in World Reference Base for Soil Resources classification: IUSS Working Group WRB [2006]), and (d) dominant aquifer hydraulic conductivity (source: Bavarian Environmental Agency, hydrogeological map 1:200,000, HÜK200) for the TERENO Pre-Alpine Observatory, represented by Ammer and Rott catchment areas.

sustain food and fodder production (Walter et al., 2012). In comparison to other ecosystems, the impacts of climate change on alpine and pre-alpine grassland soils are considered to be most critical (Beniston, 2003) due to the sensitivity of grassland soil C and N stocks to changes in temperature and rainfall, which is increased by land cover and management changes that have been imposed based on socioeconomic objectives. Both changes in climate and land cover–management of grassland soils in alpine and pre-alpine regions are likely to be accelerated in the coming decades (Beniston, 2003; Finger and Calanca, 2011). It is expected that this will induce strong changes in water and energy budgets and thus influence environmental conditions with feedback on soil, vegetation, atmospheric processes, and matter exchange. The main

long-term objectives of the TERENO Pre-Alpine Observatory thus focus on the characterization and quantification of climate change and land cover–management effects on terrestrial hydrology and biogeochemical processes at site and regional scales.

The key hydrological objectives comprise (i) improved quantification of the spatiotemporal variability of precipitation in complex terrain, (ii) investigation of soil moisture response to precipitation, and (iii) quantification of the variability, interaction, and closure of the regional interlinked water and energy cycles.

The key micrometeorological objectives are related to the biosphere–atmosphere exchange of heat, water, and CO<sub>2</sub>, with particular focus on (i) improving our understanding of atmospheric exchange processes in complex terrain, (ii) investigation

of the energy balance closure problem, and (iii) the response of net ecosystem exchange to transient climatic events.

The key biogeochemical objectives include characterization and quantification of ecosystem C and N storage, turnover, and associated biosphere–atmosphere–hydrosphere matter exchange with a particular focus on (i) GHG emissions ( $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$ ), (ii) nutrient export by seepage water, and (iii) vegetation and microbial productivity and diversity affecting ecosystem C and N transformations and losses.

## Observatory Overview and Characteristics

### Ammer and Rott Catchments

The TERENO Pre-Alpine Observatory is located in the southern part of the German federal state of Bavaria about 40 km southeast of the city of Munich. It is bound to the catchments of the rivers Ammer and Rott, both of which drain into Lake Ammer, which, at 46.6 km<sup>2</sup>, is the sixth largest lake in Germany. The observatory covers a total area of 655 km<sup>2</sup> upstream of the river gauges Weilheim (Ammer) and Raisting (Rott) (Fig. 1). Elevation ranges from 540 m asl in the north (Raisting) to 2185 m asl in the south (Kreuzspitze, Ammergau Alps). With grasslands being the dominant land cover in the valleys, the observatory includes the grassland sites Graswang, Rottenbuch, and Fendt at elevations of 864, 769, and 595 m asl, respectively. Corresponding with topography, south-to-north-oriented gradients are also prevalent for geological, pedological, and climatological properties.

Geologically, the northern part of the observatory is situated in the molasse basin of the Bavarian Alpine foreland, which extends between the Danube and the Alps. The southern part, which includes the upper part of the Ammer catchment and the Linder River, is located in the Northern Limestone Alps. From south to north, the limestone, flysch, folded Upper Freshwater Molasse, and the Lower Marine Molasse zones are traversed (Fig. 2b). Because most of the molasse area was overprinted by glacial erosion and deposition processes during the Quaternary, moraines and alluvial structures predominantly influence soil parent material conditions. The soil type distribution (Fig. 2c) is closely intertwined with the geological properties. Whereas the southern part of the observatory is characterized by Rendzic Leptosols and Calcaric Cambisols, the northern area is dominated by Cambisols, Luvisols, and Regosols. Gleysols and Histosols are found along the course of the rivers Ammer and Rott and in the areas of recent and paleo lakes. Thin and poorly permeable layers of Pleistocene and secondary Holocene deposits often cover Tertiary sediments, which are also poorly permeable. The predominant aquifers are defined by the late glacial melt water gravel and the postglacial river deposits. The predominant hydraulic conductivities for the aquifer system are shown in Fig. 2d. Due to the inhibiting Tertiary layers, many shallow aquifers have formed on top. The highest conductivity rates are found for the alluvial aquifers ( $10^{-3}$  to  $10^{-2}$  m s<sup>-1</sup>), followed by the widespread glacial gravel deposits ( $10^{-5}$  to  $10^{-4}$  m s<sup>-1</sup>) of the alpine foreland.

Lower values ( $<10^{-5}$  m s<sup>-1</sup>) are primarily bound to the geological Flysch zone and the sediment basins of major and former lakes. The alluvial aquifers of the valleys are the highest and most important aquifers in the hydrological cycle of the region. These aquifers are characterized by short to medium (hour to days) response times to precipitation events. The water tables of the alluvium and molasse aquifers (Fig. 2b) fluctuate around 0.3 to 2 m below ground. For the quaternary moraines region, the vadose zone typically extends to 3- to 30-m depth.

Hydrochemically, the groundwater belongs to the hydrogen carbonate–dominated normal earth-alkaline type. The groundwater magnesium content of the Quaternary deposits differs minimally from those of the Tertiary. Overall, sulfate, chloride, and nitrate concentrations are low, and electrical conductivities (500–900  $\mu\text{S}$ ) are typical for groundwater in lime carbonate equilibrium. The observed temperature and redox fluctuations are mainly due to a dynamic groundwater–atmosphere exchange and show very small seasonal delays (Vollers, 2016).

According to the classification of Köppen and Geiger (Kottek et al., 2006), the region of the TERENO Pre-Alpine Observatory belongs to the temperate oceanic climate. The 1981 to 2010 mean annual air temperatures (MATs) varied between 9 and 2°C for the lower areas and the mountain ridges, respectively (Fig. 3a). The MAP similarly follows the elevation gradient and ranges from 980 to 2460 mm (Fig. 3b). The average climate variables for the areas of the Ammer and Rott catchments are 7.1°C and 1430 mm yr<sup>-1</sup> for MAT and MAP, respectively. The mean discharge for the Ammer (1926–2012) is 15.3 m<sup>3</sup> s<sup>-1</sup> ( $\sim 775$  mm yr<sup>-1</sup>) and for the Rott (1951–2012) is 0.86 m<sup>3</sup> s<sup>-1</sup> ( $\sim 469$  mm yr<sup>-1</sup>).

### Characteristics of Main Measurement Sites and Basic Long-Term Observations

The spatial distribution of main and supplementary measuring sites operated by KIT/IMK-IFU within the TERENO Pre-Alpine Observatory is presented in Fig. 1. The three main sites are located along the river Ammer in the upper, middle, and lower part of the catchment. From south to north, the locations are Graswang (DE-Gwg, 864 m asl), Rottenbuch (DE-RbW, 769 m asl), and Fendt (DE-Fen, 595 m asl). These main sites are equipped with full climate and micrometeorological measuring setup and lysimeters. The DE-Fen site also features channel discharge and groundwater head monitoring, including water temperature observations. Climate characteristics at the different measuring sites are connected to elevation; thus, MAP increases and MAT decreases from DE-Fen to DE-RbW to DE-Gwg (for more details and other climate stations, see Supplemental Table S1)

The land cover at DE-Gwg, DE-RbW, and DE-Fen is grassland. The land is mainly used for fodder production for dairy cattle. Owing to local climate conditions, farmers manage DE-Gwg extensively, whereas DE-RbW and DE-Fen are managed intensively. Extensive and intensive management include up to three cuts and two manure applications and up to six cuts and five manure applications per year, respectively. Mean N loads per

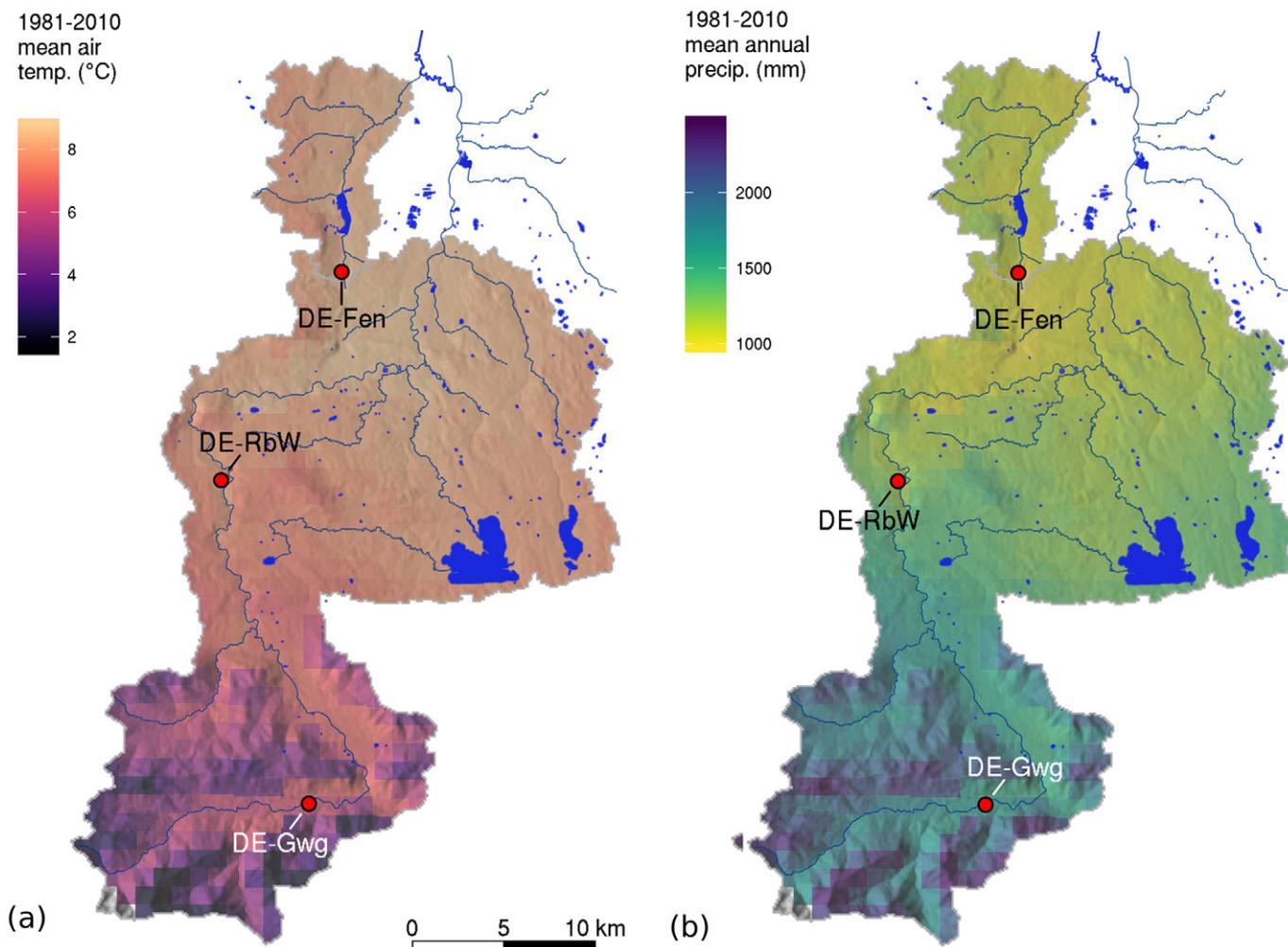


Fig. 3. Climatological averages (1981–2010) of (a) air temperature and (b) precipitation for the TERENO Pre-Alpine Observatory represented by Ammer and Rott catchment areas (data source: DWD Climate Data Center). Red dots refer to the locations of the major observatory sites.

manure event are  $42 \pm 10 \text{ kg N ha}^{-1}$  (calculated from measurements for 2011–2017), resulting in mean annual fertilization rates of about 84 and  $210 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  under extensive and intensive management, respectively.

Plant composition at DE-Gwg, DE-RbW, and DE-Fen on the level of single lysimeters has been investigated annually since 2012. Species frequency is determined within a  $0.8 \text{ m} \times 0.8 \text{ m}$  frame with 64 subsquares ( $0.1 \text{ m} \times 0.1 \text{ m}$ ). The species communities at DE-Gwg are dominated by *Festuca pratensis* Huds., *Poa pratensis* L., *Prunella vulgaris* L., *Plantago lanceolata* L., *Knautia arvensis* (L.) J.M. Coult., *Pimpinella major* (L.) Huds., and *Trifolium repens* L. Species preferring more wet conditions, like *Bistorta officinalis* Delarbre and *Polygonum bistorta* L., are present. Whereas species such as *Arrhenatherum elatius* (L.) P. Beauv. ex J. Presl & C. Presl, *Festuca rubra* L., *Lolium perenne* L., *P. lanceolata*, *P. vulgaris*, *Ranunculus repens* L., *T. repens*, and *Veronica chamaedrys* L. are characteristic of both DE-RbW and DE-Fen, *Carum carvi* L., *F. pratensis*, *Pimpinella saxifrage* L., *P. pratensis*, and *Taraxacum officinale* F.H. Wigg are dominant only at DE-Fen.

Abundance-weighted ecological species traits represented by Ellenberg values (Diekmann, 2003; Ellenberg et al., 1992) are used as indicators to characterize climatic and soil conditions at the three different sites (Fig. 4). There are no clear differences across the three sites, except that the plant community composition data suggest a gradient of increasing air temperature from De-Gwg to De-Fen, consistent with our expectations based on the climate data shown in Fig. 3a and Supplemental Table S1.

The soils at DE-Gwg are fluvic calceric Cambisols. The top 10 cm have high ( $51.7 \pm 2.5\%$ ) clay content, pH of 6.4, and bulk density of  $0.8 \text{ g cm}^{-3}$ . At DE-Gwg, the soil is rich in organic C (6.4%) and total N (0.7%). At DE-RbW, the soils are classified as cambic Stagnosol. The top soil layer (0–10 cm) is clay-loam, slightly acidic (pH 5.8), and has a bulk density of  $1.0 \text{ g cm}^{-3}$ . Compared with DE-Gwg, organic C and total N are 2.4 and 0.2% lower, respectively. Cambic Stagnosol is also found at DE-Fen. The top 10 cm is also of clay-loam texture, with pH of 5.7, bulk density of  $1.1 \text{ g cm}^{-3}$ , the lowest organic C level of 3.9%, and total N of 0.4%. More detailed soil characteristics down to 140 cm are given in Table 1.

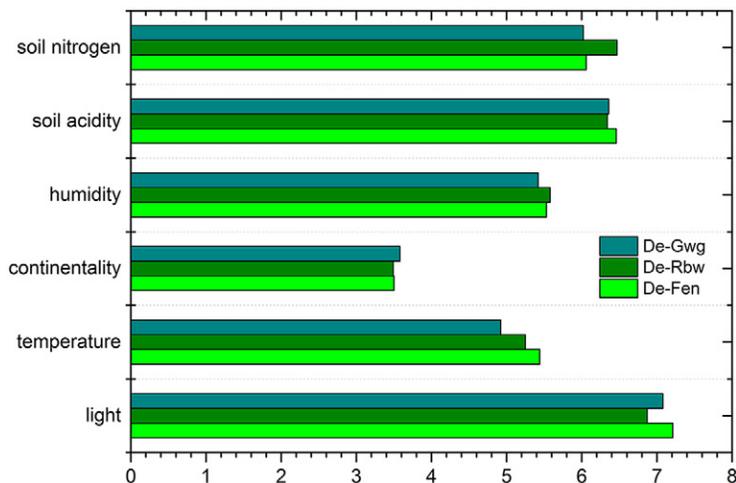


Fig. 4. Plant ecological indicators (Ellenberg et al., 1992) at DE-Gwg, DE-RbW, and DE-Fen. Values represent abundance weighted mean Ellenberg values from different lysimeters.

At supplementary sites Oberhausen-Berg (Ber, 660 m), Saulgrub-Acheleschwaig (Ach, 870 m), Oberammergau-Kolbensattel (Kol, 1270 m), and Oberammergau-Laber summit (LaS, 1680 m), only radiation, air temperature, wind, and precipitation were observed. The locations of the four climate stations were selected to extend the existing networks of the German Weather Service and the Bavarian Environmental Agency, especially for the southern region of the Ammer catchment where strong gradients prevail for climatological variables over relatively short distances

(Fig. 1). At the Geigersau site, an X-band radar is operated to detect catchment-wide rainfall patterns.

## Dedicated Long-Term Observations at Select Sites

### Micrometeorological Instrumentation

The primary mechanism for exchanging energy and air constituents between an ecosystem and the atmosphere is by turbulent motion. The most direct method to measure these turbulent fluxes is the eddy-covariance (EC) technique (Kaimal and Finnigan, 1994). To this end, turbulent time series are sampled at 20 Hz on a micro-meteorological mast at a certain height. The resulting covariance between the vertical wind velocity and a scalar to be transported—in our case temperature, water vapor, and CO<sub>2</sub>—is taken as being representative of the surface flux, assuming that the source area of this measurement is horizontally homogeneous (Aubinet et al., 2012).

Eddy-covariance measurements are conducted at DE-Gwg, DE-RbW, and DE-Fen. All three sites are located on managed grasslands, which are flat within at least a few hundred meters around the tower (Zeeman et al., 2017) (Fig. 5). Nevertheless, flux footprints of all three measurements sites were studied in detail to account for the surface heterogeneity. Footprint climatologies were determined for all three EC sites (Soltani et al., 2017), and the performance of different footprint models was evaluated using artificial tracer release experiments (Heidbach et al., 2017).

Table 1. Soil characteristics at sites DE-Gwg, DE-RbW, and DE-Fen. At all sites, soil samples were taken from undisturbed soil walls at lysimeter excavations. Measurements of soil physical and chemical properties followed standard protocols (DIN ISO 13878, 10694, 15178), and soils were classified according to the IUSS Working Group WRB (2006).

Depth	Clay	Silt	Sand	Organic C	Total N	pH	Bulk density
cm	%						g cm <sup>-3</sup>
<u>DE-Gwg: Fluvisol Cambisol</u>							
0–10	51.7 ± 2.5†	39.3 ± 0.9	9.0 ± 1.8	6.4 ± 0.6	0.7 ± 0.1	6.4 ± 0.2	0.8 ± 0.0
10–30	51.0 ± 2.5	39.3 ± 0.7	9.3 ± 2.0	1.9 ± 0.1	0.2 ± 0.0	6.8 ± 0.2	1.2 ± 0.0
30–50	50.7 ± 2.0	42.4 ± 0.9	6.1 ± 1.6	1.0 ± 0.1	0.1 ± 0.0	6.9 ± 0.2	1.3 ± 0.0
50–140	43.3 ± 1.7	37.4 ± 0.8	19.3 ± 2.2	0.7 ± 0.2	0.1 ± 0.0	7.2 ± 0.2	1.0 ± 0.1
<u>DE-RbW: Cambic Stagnosol</u>							
0–10	28.6 ± 1.7	44.8 ± 1.2	26.5 ± 1.4	4.0 ± 0.3	0.5 ± 0.0	5.8 ± 0.1	1.0 ± 0.0
10–30	29.5 ± 2.3	44.0 ± 1.1	25.8 ± 2.0	1.5 ± 0.2	0.2 ± 0.0	6.0 ± 0.2	1.4 ± 0.1
30–50	36.2 ± 3.2	42.6 ± 0.9	21.6 ± 2.9	0.6 ± 0.1	0.1 ± 0.0	6.5 ± 0.2	1.4 ± 0.1
50–140	39.8 ± 2.2	44.0 ± 0.7	16.2 ± 2.4	0.3 ± 0.0	0.0 ± 0.0	7.0 ± 0.3	1.5 ± 0.1
<u>DE-Fen: Cambic Stagnosol</u>							
0–10	30.1 ± 1.3	42.9 ± 0.9	27.0 ± 2.1	3.9 ± 0.4	0.4 ± 0.0	5.7 ± 0.3	1.1 ± 0.1
10–30	31.0 ± 2.6	42.0 ± 1.2	27.0 ± 3.5	1.6 ± 0.1	0.2 ± 0.0	5.9 ± 0.2	1.4 ± 0.0
30–50	37.5 ± 3.7	36.2 ± 2.3	26.3 ± 5.7	0.9 ± 0.1	0.1 ± 0.0	6.0 ± 0.3	1.4 ± 0.0
50–140	35.5 ± 2.8	38.1 ± 0.8	26.4 ± 2.9	0.4 ± 0.1	0.0 ± 0.0	6.4 ± 0.4	1.4 ± 0.1

† Values are means ± SD of replicated measurements ( $n \geq 3$ ).

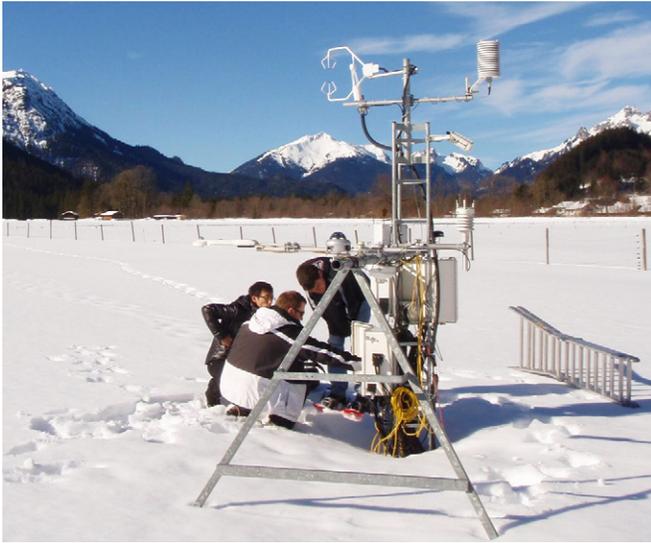


Fig. 5. Micrometeorological station at site DE-Gwg.

In addition to the EC measurement setup (CSAT-3, Campbell Scientific; LI-7500 LI-COR Biosciences), the sites are equipped to observe the full energy balance, including a four-component net radiometer (CNR 4, Kipp & Zonen), self-calibrating soil heat flux plates (HFP01-SC, Hukseflux), soil temperature and soil moisture sensors (T107 and CS616, Campbell Scientific), and basic meteorological instrumentation for measuring mean wind speed and direction, air temperature, relative humidity, air pressure, and precipitation (HMP45 and WXT520, Vaisala). A ceilometer (CL51, Vaisala) is deployed at each of the three sites to determine the height of the atmospheric boundary layer (Eder et al., 2014). The EC post-processing, including all necessary corrections, quality control, and uncertainty assessment, is conducted according to the strategy proposed by Mauder et al. (2013) using the software package TK3 (Mauder and Foken, 2015).

The TERENO sites DE-Gwg and DE-Fen are part of ICOS, a pan-European research infrastructure that provides harmonized and high-precision scientific data on C cycling and GHG budget and perturbations. We are currently approving DE-Fen for the highest ICOS level (i.e., class 1), applying mandatory EC instrumentation, verified data processing, plus strict instructions for meteorological and ancillary measurements as well as maintenance of instrumentation. The site DE-Gwg will be operated as a so-called associated ICOS site with fewer obligations.

### Lysimeter Network

The lysimeter facilities installed at DE-Gwg, DE-RbW, and DE-Fen are part of the SOILCan lysimeter network that was established between March and December 2010 as joint initiative of German TERENO partner institutions (Pütz et al., 2016). Within SOILCan, lysimeters were translocated along climate gradients within and across observatories. The underlying idea is based on the “space for time” concept (Ineson et al., 1998), which anticipates climatic change over time by a translocation of intact

soil–plant mesocosms in space. The main research focus of the lysimeter study in the TERENO Pre-Alpine Observatory is of the impact of climate and management changes on the components of grassland water, C and N cycling and budgets, biosphere–atmosphere–hydrosphere matter exchange (i.e., GHG emissions and leaching), as well as yields and biodiversity. To that end, a total of 36 intact grassland soil cores (area, 1 m<sup>2</sup>; depth, 1.4 m) were excavated and transferred to lysimeters at DE-Gwg ( $n = 18$ ), DE-RbW ( $n = 12$ ), and DE-Fen ( $n = 6$ ). Six DE-Gwg lysimeters each were transferred to DE-RbW and DE-Fen, and the remaining six were left in DE-Gwg as control (Fig. 6). Accordingly, six lysimeters each from DE-RbW were transferred to DE-Fen or remained at DE-RbW. This led to operation of 18 lysimeters at DE-Fen, 12 at DE-RbW, and six at DE-Gwg. Six lysimeters were arranged in a hexagonal structure around one service unit. At each lysimeter station, half of the lysimeters were subject to intensive management and the other half to extensive management following local farmers’ practices. After cutting events, plant biomass (dry matter) and N and C contents were analyzed.

Because the lysimeters are closed at the bottom, soil hydrology within the lysimeters is controlled by actively adjusting the lower boundary condition. This is done based on a reference water tension measurement (three replicated measurements) at the same depth (140 cm) in the undisturbed soil close to the lysimeter facility. If the water tension at 140-cm soil depth in the lysimeter is higher (i.e., wetter) than the reference, water is pumped out into a tank via an underpressurized suction rake. The opposite procedure occurs when the soil inside the lysimeter is drier than outside conditions, which has rarely been the case due to overall high amounts of rainfall and low groundwater tables.

For each single lysimeter, rates of water balance components (i.e., precipitation, actual evapotranspiration, and seepage water) are derived from precision weighing (load cells Model 3510, Teda Huntleigh, with 10-g resolution equal to 0.01-mm precipitation) of lysimeters and water tanks, acquired in 1-min time intervals. In all lysimeters, volumetric water content (time domain reflectometer CS610, Campbell Scientific), water tension, and soil temperature (SIS, METER Group) were measured at depths of 10, 30, 50, and 140 cm (TS1, METER Group). Soil water was collected by suction cups (SIC20&VS PRO, METER group; 100 hPa for 10, 30, and 50 cm and 200 hPa for 140-cm soil depth) at the same depths and stored in 1-L dark glass bottles mounted in the service unit. Water samples were collected bi-weekly and analyzed for NH<sub>4</sub>, NO<sub>3</sub>, dissolved organic N, and dissolved organic C.

Soil GHG exchange of CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> was measured by the static chamber approach at DE-Fen and DE-RbW by robotic systems that move on rails sequentially from lysimeter to lysimeter and lower a rubber-sealed static dark chamber on top of a collar at each location for a closure time of 15 min (Fig. 7).

Ecosystem respiration (Reco) and biosphere–atmosphere exchange of N<sub>2</sub>O and CH<sub>4</sub> were determined at subdaily time resolution (four fluxes per lysimeter and day) by measuring the headspace GHG concentration increase using Quantum Cascade

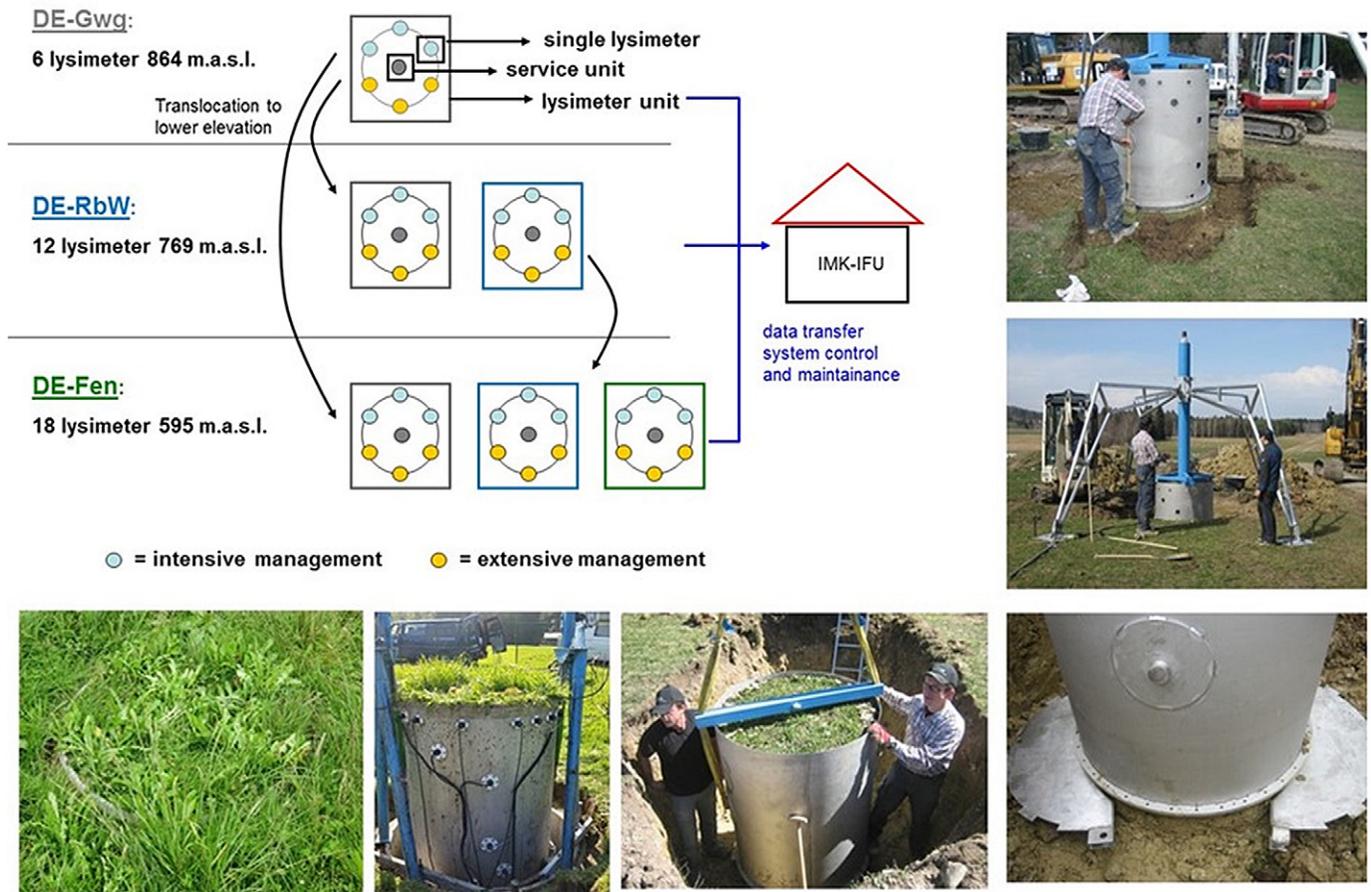


Fig. 6. Scheme of lysimeter excavation, translocation, and operation at sites DE-Gwg ( $n = 6$ ), DE-RbW ( $n = 12$ ), and DE-Fen ( $n = 18$ ) within the TERENO Pre-Alpine Observatory.

Laser Absorption Spectroscopy (QC-TILDAS\_DUAL, Aerodyne Research). At DE-Gwg, manual chamber measurements were performed at least weekly and at least three consecutive days after fertilization and frost-thaw events. Here, chamber headspace concentrations of a set of six lysimeters were sampled five times over a closure period of 45 min. Samples were transferred into vials,

which were analyzed for GHG concentration by gas chromatography (flame ionization detector and electron capture detector) in the laboratory. Since summer 2018, DE-Gwg has been equipped with an automatic robot system. Here and at DE-Fen, the dark chamber measuring system was equipped with a LED system, allowing measurement NEE at various adjustable light levels.



Fig. 7. Overview of the robotic chamber system at site DE-Fen.

## Soil Moisture Network

Since June 2015, spatially distributed measurements of soil moisture, temperature, and matrix potential have been performed at DE-Fen with the wireless underground sensor network SoilNet, which was developed specifically for the near real-time monitoring of the spatiotemporal dynamics of soil water content at field and headwater catchment scales by Forschungszentrum Jülich GmbH (Bogena et al., 2010). The SoilNet at Fendt comprises 55 measurement profiles distributed over a total area of about 300 by 300 m, with 20 profiles being distributed along a regular 70- by 70-m grid and 35 profiles being randomly scattered to provide adequate spatial coverage and to facilitate geostatistical analysis of the data. Measurements are performed at depths of 5, 20, and 50 cm in a temporal resolution of 15 min. At each depth, one dielectric soil water potential sensor (MPS-6, Decagon Devices) and two electromagnetic soil water content sensors (SMT100, Truebner GmbH) were installed horizontally into the soil (~5–10 cm from each other). In addition to soil water potential and water content, both sensors record soil temperature. This redundant setup with several sensors per depth allows the examination of the data for small-scale heterogeneity and inconsistencies (e.g., due to the formation of cracks around individual sensors).

After each measurement, data were transmitted via radio transmission ( $f=2435$  MHz) from the sensor units to a so-called coordinator. From the coordinator, data were passed on to a COM server, which allows direct access to the data via the Internet. For more detailed information, see <http://www.soilnet.de>.

## Cosmic-Ray Neutron Sensors

From the neutron sensor measurements, soil moisture and snow water variations can be observed within a multihectare footprint size. In TERENO Pre-Alpine, a network of four stationary sensors is operated at DE-Fen, Ach, DE-Gwg, and Esterberg (adjacent to the TERENO Pre-Alpine region, 47.51642 latitude, 11.15773 longitude). The site elevations follow a gradient from 600 to 1270 m asl. Each site is equipped with a bare and a moderated CRS-2000B sensor (Hydroinnova Inc.) and an additional measurement device for air pressure (onboard the datalogger), temperature, and humidity (CS215, Campbell). The recording interval for all variables is 10 min (QI-DL-2100 data logger, Quaesta Instruments), and data are transferred by cellular telemetry. The DE-Fen device is situated in the center of the 55 soil moisture network profiles.

## Remote Sensing by X-Band Radar

Since June 2009, a single polarization X-band rainfall radar (Selex ES GmbH) has operated a 16-m mast at the Geigersau site (955 m asl) (Fig. 8). Its 90-cm antenna detects the backscatter signals of precipitation at 3° elevation in high temporal and spatial resolution of 12 scans  $\text{min}^{-1}$  and 2° by 100-m azimuthal sectors, respectively. Before further processing, the 5-min medians of the raw DbZ data are filtered for corrupted data or artifacts. The qualified data are then converted to standard NetCDF format (NETCDF4\_CLASSIC), stored at the TEODOOR database, and

post-processed using adopted wradlib routines (Heistermann et al., 2013). This includes the removal of static noise signals (e.g., nearby ground clutter, obstacle clutter caused by the mountains, or wet random effects) (Bechini et al., 2010).

Especially at X-band frequency, the crucial challenge of single polarization radars is the proper attenuation correction to get a correct quantitative precipitation estimation (Kraemer and Verworn, 2008). To correct for this attenuation bias, the X-band hourly rainfall sums, >10 km away from the radar, are adjusted to an extract of 2% of the 1-km resolution RADOLAN from the German Weather Service (Bartels et al., 2004). This procedure results in improved agreement toward the gauge measurements provided by the TERENO climate stations, the German Weather Service, and the Bavarian Flood Warning Service. Preliminary results indicate that this corrected X-band radar rainfall data, with its high spatial-temporal resolution, can improve the skill of hydrological modeling for the Ammer catchment with respect to the lower resolution RADOLAN data.

## Specific Campaigns, Experiments, and Projects ScaleX

ScaleX is a series of collaborative, intensive research campaigns that assess spatially distributed patterns and gradients in land surface–atmosphere exchange processes within the TERENO Pre-Alpine Observatory and specifically surrounding the DE-Fen site (Wolf et al., 2017; <https://scalex.imk-ifu.kit.edu/>). Unique to ScaleX is the focus on interdisciplinary links in processes in



Fig. 8. X-band radar at TERENO pre-alpine site Geigersau.

complex terrain that emerge at the submesoscales when bridging observations and models. The research objectives focus on scale integration, which is achieved using novel methodologies at the interfaces of soil, vegetation, and atmosphere. ScaleX augments the observations made by the permanent TERENO infrastructure with observations of increased spatial and temporal resolution and increased spatial domain. ScaleX campaigns took place in 2015 and 2016, and a further one is planned for 2019. During the two past campaigns, researchers teamed up to evaluate the spatial variability of precipitation, surface energy exchange, the source strength of GHGs, the influences of local air-flow patterns, and sensor design. The additional experiments included innovative systems for concerted airborne sampling and land-surface sensing (Brenner et al., 2018; Brosy et al., 2017; Golston et al., 2017; Mauder and Zeeman, 2018), ground-based remote sensing and mobile survey platforms, and enhanced sampling strategies to resolve properties of the atmospheric boundary layer, turbulent exchange, precipitation, the soil, and vegetation. The ScaleX activities therefore contribute to the evaluation of methodologies that are fundamental to the observatory and to the development of model chains that aim to resolve submesoscale interactions.

## Rainfall Observation Using Commercial Microwave Link Networks

Due to the high spatiotemporal variability of precipitation, its accurate estimation is challenging. In particular, in mountainous terrain, rain gauges and weather radars are limited in providing reliable observations. A promising new technique that helps improve rainfall estimation is the use of attenuation data from commercial microwave link (CML) networks, which are used to provide a large part of the backhaul of the cell phone network (Messer et al., 2006). These CMLs, which interconnect the cell phone base stations, are typically between 1 and 20 km and operate in the frequency range of 15 to 40 GHz. In this configuration, the signal along the path of a CML experiences strong attenuation due to precipitation. Hence, measurements of the attenuation can be used to calculate the rainfall rate along the path. In comparison to rain gauge observations, these line-integrated measurements have a better spatial representativeness. In comparison to weather radar observations, the CML measurements are near the ground (typically several tens of meters above), and the CML's relation between rain rate and measured attenuation is much more robust than the radar's relation between rain rate and measured reflectivity. Together with the large number of CMLs (e.g., ~150,000 in Germany), they provide a very good complement to rain gauge and radar observations.

To accompany our research on rainfall estimation via CMLs, we have developed a dedicated microwave transmission device to study the relationship between precipitation and microwave propagation in more detail. The system operates two frequencies (22.235 and 34.8 GHz) and two polarizations in parallel, providing the option to analyze differential measurements, which provide more insight into the precipitation drop size distribution and error

sources like antenna wetting (Chwala et al., 2014). Together with two disdrometers, the system is installed at the TERENO field site Fendt. A follow-up system has been developed that will allow a more detailed analysis of the wet antenna effect (Moroder et al., 2017) and extend the frequency range to cover all common frequencies of CMLs.

Within the project “Integrating Microwave Link Data for Analysis of Precipitation in Complex Terrain: Theoretical Aspects and Hydrometeorological Applications” (IMAP, funded by the German Science Foundation), KIT/IMK-IFU acquires data of more than 4000 CMLs in Germany, in cooperation with Ericsson as CML network operator (Ericsson Deutschland GmbH). Of these, 12 CMLs are located within the TERENO Pre-Alpine Observatory. Once every minute, data are delivered in real-time to a KIT/IMK-IFU server (Chwala et al., 2016) and further processed to derive rain rates from the partly noisy raw data. This is done via our own (Chwala et al., 2012) and other published methods (e.g., Schleiss et al., 2013) integrated and available in our open-source processing toolbox `pycomlink` (<https://github.com/pycomlink/pycomlink>). With the several CMLs that are available in the Ammer catchment, we have shown that integrating CML-derived rainfall information into a hydrological model considerably improves runoff simulation for a major flood event (Smiatek et al., 2017). Future work will focus on increasing the number of CMLs that are included in the data acquisition process, providing CML-derived rainfall information in near real-time, and deriving spatial rainfall information in combination with weather radar data (Haese et al., 2017).

## Helmholtz Young Investigator Group

The TERENO Pre-Alpine Observatory was the main study area of the Helmholtz Young Investigator Group led by Dr. Matthias Mauder with the topic “Capturing all relevant scales of biosphere-atmosphere exchange—the enigmatic energy balance closure problem.” Even with the most direct and advanced measurements, it is generally not possible to close the energy balance at the Earth's surface, although this is the main interface for absorption of solar radiation. A greater part of the solar energy input is transported by means of turbulent motion into the atmosphere in the form of sensible and latent heat. However, state-of-the-art worldwide observations show a general underestimation of these turbulent heat fluxes by about 15% on average compared with the available energy. This energy balance closure problem has been known for more than 25 yr, and a general solution has not been found. It is widely acknowledged that this problem represents a major impediment for progress in atmospheric, climate, and ecosystem sciences.

The problem arises in modeling and observational studies because a fundamentally four-dimensional process is analyzed in a simplified one-dimensional framework, assuming horizontal homogeneity, stationarity, and isotropic turbulence. Although the simplified analysis is sufficient to explain the turbulent transport by small-scale eddies, large-eddy transport in particular violates all of these conditions and therefore cannot be captured by standard

techniques. Hence, a paradigm shift is necessary to address this issue, combining novel experiments and simulations, so that the whereabouts of the missing 15% of the solar energy input will be elucidated.

The Helmholtz Young Investigator Group aimed for an improved understanding of the large-eddy transport expressed in form of a semi-empirical parameterization. To this end, numerical methods were developed to investigate atmospheric transport processes systematically under controlled conditions in a large-eddy simulation domain. Several field campaigns were conducted using EC together with ground-based remote sensing instrumentation. Two existing parameterizations for the unaccounted energy fluxes were evaluated using these field data (Eder et al., 2014). A correlation analysis of observational data helped to identify potential parameters for a semi-empirical model. Hence, the most important parameters are the friction velocity and the vertical gradients of temperature and humidity in the convective boundary layer (Eder et al., 2015). A formulation for the systematic error related to the energy balance closure problem was proposed (Mauder et al., 2013). This energy balance closure adjustment was evaluated using the nearby lysimeter measurements as an independent reference (Mauder et al., 2018). A generalized large-eddy simulation study of the effect of the dominant scale of the horizontal heterogeneity on the atmospheric transport processes leading to the energy balance closure problem was conducted (De Roo and Mauder, 2018).

## SUSALPS

SUSALPS ([www.SUSALPS.de](http://www.SUSALPS.de)) is an integrative project funded by the German Federal Ministry of Education and Research. It has a long-term perspective (2015–2021) and aims to provide a holistic, evidence-based, and process-focused understanding of the responses of key pre-alpine and alpine grassland soil functions to present-day and future climate and land management changes. SUSALPS makes use of and expands the hydrological and biogeochemical monitoring program in the TERENO Pre-Alpine Observatory by including further partners and combining fields of soil and plant ecology (Technical University Munich, University of Bayreuth), soil biogeochemistry (Helmholtz Zentrum München), and agronomy and socio-economy (University of Bayreuth) as well as expert knowledge of the Bavarian State Research Centre for Agriculture. SUSALPS experimental work quantifies the impacts of climate and land management changes on plant and microbial diversity, nutrient use efficiencies, biomass production and quality, soil C and N storage and turnover, GHG emissions, and nutrient leaching at several sites in the TERENO Pre-Alpine Observatory. Results are used (i) to develop early warning systems (agri-ecological indicators) indicating potentially negative impacts on grassland ecosystems and (ii) to inform and validate biogeochemical models that are used in scenario studies to evaluate best management options for sustainable use of grassland ecosystems. To allow the assessment of joint socioeconomic impacts of current and climate smart grassland management practices, the KIT/IMK-IFU biogeochemical model LandscapeDNDC (Haas et al., 2013) is coupled to a socioeconomic model.

will be further developed into a decision support system, which will help stakeholders and farmers to understand the consequences of grassland management on soil functions and other ecosystem services and to optimize grassland management.

## Data Management and Policy

Data management and policy in the TERENO Pre-Alpine Observatory are regulated by the TERENO data management plan (<http://teodoor.icg.kfa-juelich.de/downloads/DMP-V1.0.pdf/view>) and the TERENO data policy (<http://teodoor.icg.kfa-juelich.de/downloads/TERENO%20Data%20policy.pdf-en/view>), jointly developed by all institutions involved in the TERENO program ([www.tereno.net](http://www.tereno.net)). Basic long-term observations and data originating from the lysimeter network, soil moisture network, and X-band radar are accessible via the TERENO data portal TEODOOR (<http://teodoor.icg.kfa-juelich.de/ibg3searchportal2/index.jsp>).

Micrometeorological measurements conducted at Graswang (DE-Gwg), Rottenbuch (DE-RbW), and Fendt (DE-Fen) are shared through the European Fluxes Database cluster ([www.europe-flux-data.eu/](http://www.europe-flux-data.eu/)).

## New Insights and Novel Scientific Findings Impact of Climate Change on Grassland Nitrogen Cycling and Leaching Losses

Multiyear data of the grassland lysimeter network (Fu et al., 2017) show that at DE-Fen, the site with highest mean annual air temperature (8.6°C) and the lowest mean annual precipitation (958 mm), annual evapotranspiration losses (656 mm) were significantly higher and annual seepage water formation (306 mm) significantly lower than at DE-Gwg and DE-RbW located at higher elevations. Compared with climate, the impacts of grassland management on water balance components were insignificant. Independent of differences in seepage water formation due to higher loads of N fertilization intensive management significantly increased total N leaching rates compared with extensive management across all sites. Overall, annual N leaching losses were rather small (0.5–12.9 kg N ha<sup>-1</sup>) and were dominated by nitrate. The low rates of N leaching and N<sub>2</sub>O emissions (Unteregelsbacher et al., 2013) suggest a highly efficient N uptake by plants, as reflected by high total N export at harvest, partly even exceeding slurry N application rates. This indicates substantial plant N supply via the mineralization of soil organic matter. Soil mesocosm translocation studies further show that climate change conditions more than double gross N mineralization in grassland top soils (Fig. 9), which mainly supports further plant growth but has no significant effects on N leaching rates (Wang et al., 2016).

Thus, the risk of nitrate leaching and surface runoff of ungrazed grassland is low both under current and climate change conditions (on loamy/clayey soils with vigorous grass growth). This finding may call for a careful site- and region-specific

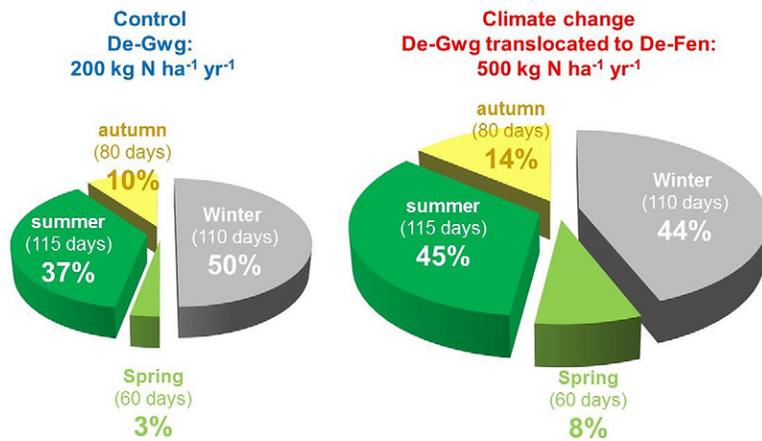


Fig. 9. Gross N-mineralization rates (0–10 cm soil) of sites DE-Gwg “control” and DE-Gwg “climate change” (i.e., DE-Gwg translocated and operated at DE-Fen) (Wang et al., 2016).

reevaluation of N-fertilization limits (Fu et al., 2017). Such limits are defined by, for example, the German Fertilizer Ordinance (Düngeverordnung, 2017), following requirements set by the European Water Framework and Nitrates Directives (European Economic Community, 1991). However, over the long term, climate-change-induced increases in mineralization rates are likely to result in soil organic matter losses, with negative impacts on key soil functions and grassland productivity.

### Response of Upland Grasslands to Reduced Snow Cover and Its Relation to Changing Global Circulation Patterns

The 2013/2014 winter season showed exceptionally sparse snow cover conditions north of the Alps, which allowed an in situ investigation of the response of vegetation to changed environmental conditions (Zeeman et al., 2017). Examination of CO<sub>2</sub> fluxes along an elevation gradient from 600 to 860 m asl revealed that elevation, snow cover extent, and soil temperature and management were determinative factors for productivity. In the absence of snow cover at the highest elevation site (864 m), substantial growth started only when the mean daily soil temperature exceeded 5°C, whereas the vegetation at the lowest elevation site (595 m) remained photosynthetically active throughout the winter. The reduced snow cover at the lower elevation sites (595 and 769 m) resulted in a significant increase in gross ecosystem production and ecosystem respiration as well as enhanced CO<sub>2</sub> uptake. The reduced snow cover in the 2013/2014 winter season can be attributed to an increase in Föhn frequency, which in turn can be related to a general change in global circulation patterns. Comparing the highest Föhn years relative to the lowest of the last 35 yr in reanalysis-based 500 hPa geopotential height significant anomalies reveals a different pressure dipole than the traditional Arctic Oscillation or North Atlantic oscillation. Observations from 11 sites across the Alps show that as much as 86% of the variation in spring gross ecosystem production can be explained by winter Föhn frequency (Desai et al., 2016).

### Use of Commercial Microwave Links for Precipitation Quantification and Potential for Improved Hydrological Modeling

The spatiotemporal variability of precipitation is still one of the crucial uncertainties that hydrological modeling efforts have to cope with. Particularly in mountainous terrain or in regions with coarse station networks, hydrological modeling can benefit tremendously from innovative new methods for precipitation quantification. The TERENO Pre-Alpine Observatory was the testbed for the evaluation of the potential of CML-derived precipitation estimates in distributed hydrological modeling (Smiatek et al., 2017). Commercial microwave link networks allow for the quantification of path-integrated precipitation because the attenuation by hydrometers correlates with rainfall between transmitter and receiver stations. The networks, operated and maintained by cell phone companies, provide new and countrywide precipitation measurements. The additional value of CML-derived rainfall estimations combined with station observations was compared with station- and weather radar-derived values. This was achieved by applying the distributed hydrological model WaSiM in 100- by 100-m<sup>2</sup> resolution to the catchment of the river Ammer for two episodes of 30 d with typically moderate river flow and an episode of extreme flooding. A significant improvement in hydrograph reproduction was achieved in the extreme flooding period that was characterized by a large number of local strong precipitation events (Fig. 10). The present rainfall monitoring gauges alone were not able to correctly capture these events (Smiatek et al., 2017).

### Spatiotemporal Variability of Coupled Water and Energy Fluxes

Due to its unique variety of observed hydrologically relevant variables, the observatory is an ideally suited testbed for hydrological models, particularly physically based model systems that account for the complex interplay of fluxes and variables. It served as testbed for the investigation of the spatiotemporal variability and dependence structure patterns of water and energy fluxes along its elevation gradient (Soltani et al., 2018). The analysis applied the GEOTop model (Endrizzi et al., 2014; Rigon et al., 2006) and extended the studies of Hingerl et al. (2016) and Soltani et al. (2017) by using both GEOTop model results and the concept of empirical copulas for a multivariate dependence structure analysis. It was performed for both the Rott and the Upper Ammer catchments. GEOTop was capable of quantifying the spatiotemporal variability of the water and energy budgets with consideration for the elevation gradient effect of this heterogeneous landscape. The daily cycle of multiple-layer soil moisture variations was appropriately described by the model. The EC-based diurnal cycles of energy fluxes (latent heat, sensible heat, and ground heat) were well reproduced by GEOTop; however, the model slightly overestimated LE, especially during the early morning due to the lack of energy balance closure in the EC-based measurements

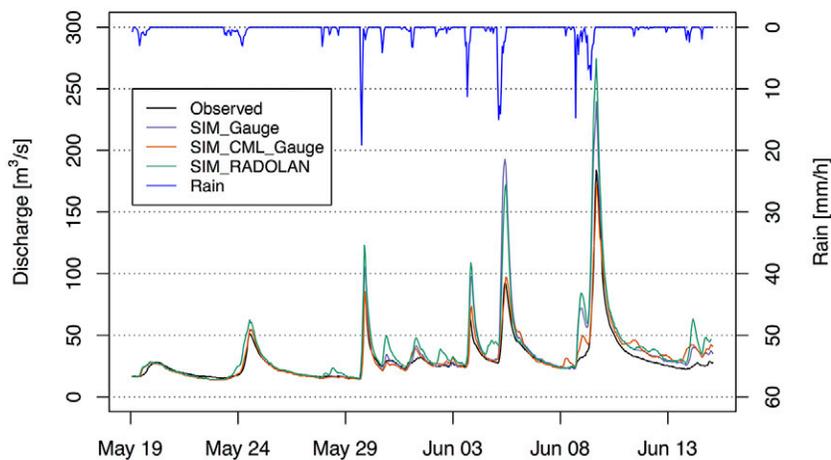


Fig. 10. Observed and simulated runoff for the river Ammer at the discharge gauge Weilheim (Am-WM in Fig. 1). The different simulations (SIM\_GAUGE, SIM\_CML\_Gauge, and SIM\_RADOLAN) used rainfall input from gauges, commercial microwave links and gauges, and the RADOLAN weather radar product, respectively. The shown rainfall is the mean catchment rainfall from SIM\_Gauge. This plot is based on Smiatek et al. (2017).

(imbalance of 31% at Fendt and 39% at Rottenbuch). The spatial distributions of water and energy fluxes revealed that, in the Upper Ammer catchment,  $\sim 70\%$  of precipitation leaves the catchment as discharge, compared with  $\sim 10\%$  in Rott. Approximately 30% of net radiation leaves the Upper Ammer catchment as sensible heat fluxes, compared with only  $\sim 15\%$  in Rott. The bivariate dependence structure patterns of both measured and simulated hydrometeorological variables considered in this study are very similar, representing a reasonable calibration of the GEOTop model. These nonlinear features in the dependence structure of measured and simulated individual hydrometeorological variables were observed with the highest densities (or best fit between the modeled and observed values) either in the lower or upper ranks (i.e., in the low or high values) but exhibited a worse model calibration for the middle ranks of the data.

### Multicopter-Based Air Sampling and Sensing of Meteorological Variables

The comprehensive instrumentation of the TERENO Pre-Alpine DE-Fen site and its massive completion during the ScaleX campaigns was most useful for testing and performance analysis of unmanned aerial vehicle (UAV)-based sensing of meteorological variables in the atmospheric boundary layer. A multicopter-type UAV was applied for spatial sampling of air and simultaneous sensing of meteorological variables to characterize surface exchange processes (Broisy et al., 2017). The UAV was equipped with onboard air temperature and humidity sensors, and 3-dimensional wind conditions were determined from the UAV's flight control sensors. The UAV was also used for distributed methane measurements. This was achieved by systematically changing the location of a sample inlet connected to a sample tube, allowing the observation of methane abundance using a ground-based analyzer. The results showed that methane concentrations and meteorological conditions were in agreement with other observations at the site during the ScaleX-2015 campaign. The RMSE of true air speed was  $\pm 0.3 \text{ m s}^{-1}$ . In the case of methane, the RMSE was  $\pm 0.063 \text{ ppm}$ . Consequently, the measurements on the moving platform were as representative as those of the stationary tower installation.

### Lessons Learned and Future Perspectives

The setup of the measuring infrastructure in the TERENO Pre-Alpine Observatory started in 2009 with an initial focus on micrometeorological and lysimeter stations at the three main sites (DE-Gwg, DE-RbW, and DE-Fen) and with the establishment of the X-Band radar. These sites, and further locations of traditional climate stations, were selected based on a detailed biophysical and instrumentation survey in the Ammer catchment to ensure representativeness and suitability of sites for environmental research and to complement the pre-existing observation networks run by the German Weather Service (weather stations) and the Bavarian Environmental Agency (streamflow discharge gauges). Since then, the measuring infrastructure has been growing steadily, with an increasing number of national and international governmental and university partners continuously contributing to long-term observations and surveys and/or participating in dedicated measuring campaigns or third-party projects. Overall, this development allowed KIT/IMK-IFU and its partners to work jointly on diverse meteorological, hydrological, and biogeochemical research questions and interactions as well as on feedback among these scientific fields. This process is in line with the propagated "deep science" framework for critical zone observatories (Guo and Lin, 2016), which highlights the need for interdisciplinary compartment-crossing research (deep coupling) at multiple spatial scales (deep depth) and time scales (deep time). Whereas deep depth and deep time are rather straightforward in many research disciplines, deep coupling is much more challenging. In our experience, joint measuring campaigns involving different research disciplines at the institutional level (KIT/IMK-IFU), within national networks (e.g., TERENO), and in cooperation with national and international partners (e.g., ScaleX campaign; Hörtnagl et al., 2018), are most fruitful to achieve this goal. Furthermore, the integration of TERENO Pre-Alpine sites into international observation programs such as ICOS or FLUXNET increased the visibility of the observatory both in Europe and globally. Overall, such initiatives stimulate not only the close collaboration of experimentalists but also the interaction with modelers. Comprehensive long-term

integrated observations in different compartments (atmosphere, hydrosphere, biosphere) of the terrestrial system are used to set up, further develop, and apply various process models for site- and regional-scale or catchment-scale simulations. The evaluation of the energy balance closure problem for evapotranspiration estimates (Mauder et al., 2018) and the methodology development to use commercial microwave links for precipitation quantification and improved discharge modeling (Smiatek et al., 2017) are prominent examples. TERENO Pre-Alpine observations have been used in conjunction with physically based process models to examine the impacts of land cover–management and climate change on ecosystem-atmosphere cycling of energy (e.g., large-eddy simulation model PALM; Maronga et al. [2015]), water (e.g., WaSiM and GEOtop; Kunstmann et al., 2006), as well as C and N (e.g., LandscapeDNDC; Haas et al. [2013]).

Because the setup, calibration, and validation of such models requires much more than plot- to field-scale observations (particularly for upscaling from site to regional and catchment scales), advanced methods of nonlocal observations and data-model fusion need to be developed. Over the last few years, drones and satellites (e.g., Sentinel 1 and 2) have constituted a new family of Earth observation techniques, with an unprecedented temporal, spatial, and spectral resolution as well as data coverage scheme. Through the synergetic use of radar and multispectral data and advanced remote sensing signal processing algorithms, the development of new plant and soil monitoring applications is enabled. Due to the spread of TERENO Pre-Alpine sites along an elevation gradient, in situ measurements of vegetation (e.g., plant biomass and fractional coverage) and soil properties (e.g., soil moisture) can ideally serve as ground-truth and to evaluate derived remote sensing products. Thus, ground-based measurements will be increasingly supported with remote sensing techniques and products that serve for initialization of land surface properties in models and help to characterize the temporal variation of plant (including, e.g., management) and soil states on regional/catchment scales. The integration (e.g., initialization, data assimilation, validation) of satellite and drone-based observations into hydrological, biogeochemical, and regional Earth-system models allows also for reducing modeling uncertainties, particularly at the regional scale (e.g., via improved model initialization and validation). This is expected to be beneficial also for a wide range of practical applications, including high-resolution weather predictions, flood forecasts, yield predictions, estimates of ecosystem C sequestration, and quantification of the environmental footprint (e.g., GHG emission and nutrient leaching) of agricultural production. Thus, the integrated measuring and modeling strategy of the TERENO Pre-Alpine Observatory does not only serve science with improved process understanding (of impacts of climate and land cover–management changes on energy; water and matter cycling; and related regulating, provisioning, and supporting ecosystem services); linked to demands of stakeholders and the public, it can also stimulate the development of applied recommendations and forecasts (e.g., by decision support tools used for optimized,

weather-adapted agricultural management), which are essential for the development of mitigation and adaptation strategies (together with socioeconomic studies on costs and acceptance).

Our experience gained by designing, setting up, and operating the TERENO Pre-Alpine Observatory was the prerequisite to establish the hydrometeorological WASCAL Observatory under much stricter logistical constraints in the West African Savanna (Bliefernicht et al., 2018), funded by the German Federal Ministry of Education and Research. In close cooperation with African scientists and engineers, instrumentation and data procedures for water, energy, and C flux monitoring were set up similar to the TERENO concept. Moreover, first steps toward continuous CML-based precipitation quantification were made in a region of the West African Sahel, where conventional observations of precipitation are virtually nonexistent. All actions were supported by international training workshops on the relevant topics (e.g., Gosset et al., 2015). Thus, the TERENO Pre-Alpine Observatory has achieved scientifically and societally relevant capacity building, even into regions of scarce technical infrastructure such as West Africa, where adaptation to climate change in the fields of water management and land use is of utmost importance for long-term sustainable development.

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