WegenerNet

A Pioneering High-Resolution Network for Monitoring Weather and Climate

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The Wegener Center of the University of Graz in Austria is operating a novel climate station network at 1-km-scale resolution that serves as a long-term monitoring and validation facility for research and applications.

I t all began in spring 2005 with a discussion in the newly founded Wegener Center for Climate and Global Change at the University of Graz (www.wegcenter.at) on how to validate regional climate models (RCMs), commonly still used at 10–50-km resolution (Maraun et al. 2010; Foley 2010), if we increasingly pursue to operate them at 1–10-km resolution. At this resolution, nonhydrostatic and convection-resolving modeling allows more realistic simulations, especially for regions with mountainous or hilly terrain (Hohenegger et al. 2008; Awan et al. 2011; Suklitsch et al. 2011; Prein et al. 2013b).

In addition to this question, which came from the aim to evaluate high-resolution RCM fields obtained from dynamical downscaling of global climate model simulations to regional and local scales (Prein and Gobiet 2011; Prein et al. 2013a), a similar question arose on how to validate high-resolution products from statistical downscaling techniques (Maraun et al. 2010; Themeßl et al. 2011). And, third, there was the question on how to better validate remote sensing observations at 1-km-scale resolution, such as weather radar data and high-resolution data from meteorological satellites (e.g., Morin and Gabella 2007; McLaughlin et al. 2009; Roebeling and Holleman 2009).

Finding the interest in tackling these validation questions furthermore matched by a strong complementary interest to better characterize weather and climate processes at 1–10-km scales—including their interplay with factors such as orography, land cover and its changes, and hydrological dynamics—the avenue became clear rather quickly: the newly founded Wegener Center, for which an innovative field activity would anyway be a meaningful outlet both scientifically and for promoting awareness of weather and climate science in the interested public, wants to undertake a pioneering long-term field experiment by deploying a dense grid of

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meteorological stations. It should be placed in a suitable region with a rich variety of weather and climate patterns and feature near-1-km average station distance in an area of about 20 km × 20 km, covering the much needed 1–10-km-scale range. Thus, the WegenerNet was born by May 2005—as an idea.

Figure 1 shows what we then actually realized, essentially over mid-2005 to the end of 2006, as the WegenerNet climate station network Feldbach region in the Alpine foreland region of southeastern Austria (details of setup and reasons for region selection are discussed further below). Table 1 summarizes the main network characteristics. Regular measurements started in 2007, so that we can report here from at least five full years of data from the period 2007–11. The various RCM modeling domains enclosing the

WegenerNet region in Fig. 1a are shown to indicate its utility for helping validate dynamical and statistical downscaling results at 1–10-km scales and aiding calibration and improvement of underlying RCMs or statistical models. The 151 stations, with an average station distance of about 1.4 km over a total area of about 300 km² (150 grid cells of size 2 km², see grid in Fig. 1b), continuously measure temperature, precipitation, and other parameters with 5-min time sampling. The data are available to users in near–real time with less than 1–2-h latency.

After a pilot phase from 2007 to 2010 and the subsequent establishment of a long-term operations perspective, we provide here a first overall introduction of the WegenerNet to the broad international community, aimed at being informative to researchers
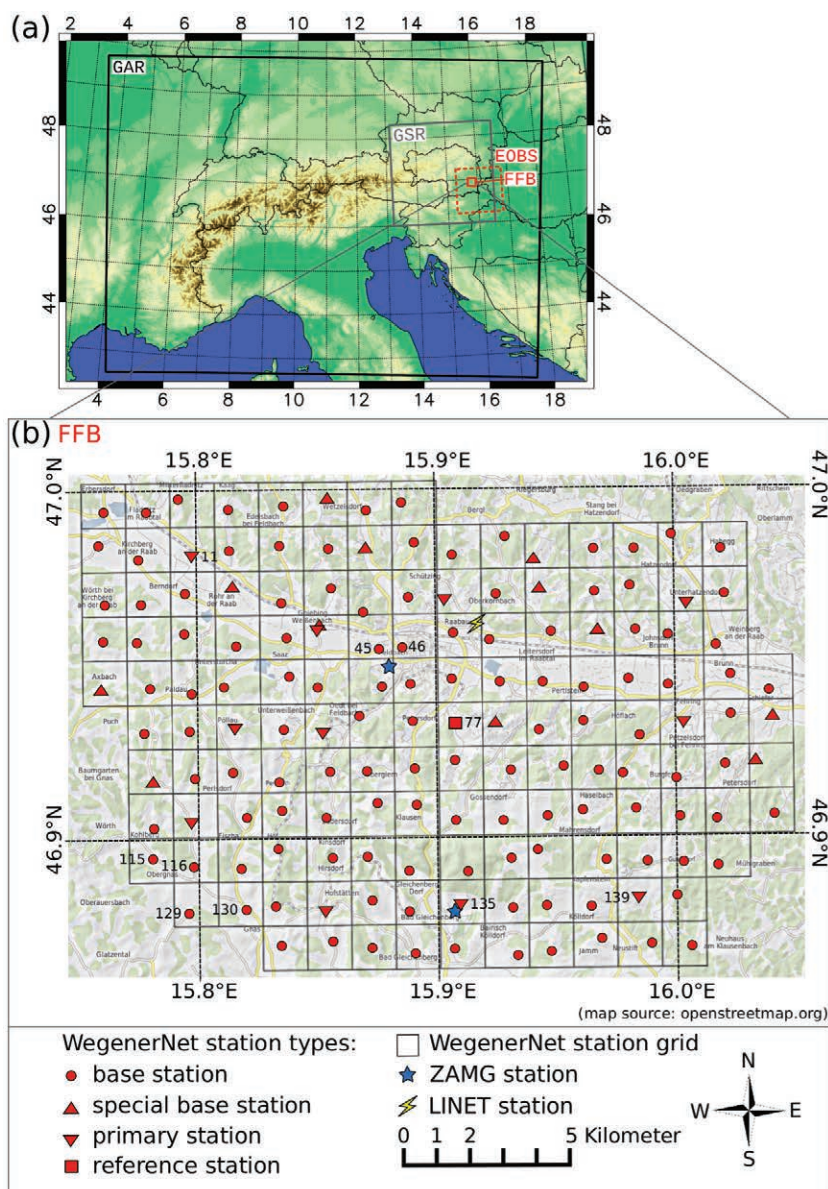
Fig. 1. The WegenerNet region in southeast Austria as part of the greater Alpine region (GAR). (a) The GAR includes Austria, marked by its national borders, and the greater Styrian region (GSR) encompassing the state of Styria, marked by its state borders. In southeastern Styria, the focus Feldbach region (FFB; red rectangle) comprises the WegenerNet area [enlarged in (b)] around which a further region of about 100 km × 100 km size, used for intercomparison to E-OBS data, is indicated (dashed red rectangle). In addition to showing geographical context, these regions are climate model domains for dynamical downscaling from GAR to FFB as employed in the modeling example application of Fig. 10. (b) The WegenerNet region is about 20 km × 15 km size with its 151 stations, illustrating also station types and complementary stations; for more information on station characteristics see Table 1. The backdrop map indicates the hilly landscape of the region (with a moderate altitude range from about 260 to 520 m). The river Raab valley (gray broad band from northwest to east) and a series of smaller streams joining into the Raab are the main features determining the orography (a complementary view on this orography is available in Fig. 10).

and other professional peers but also to high school educators and general weather enthusiasts alike (from its phasing in at the national level, the network has more than scientific users—also hundreds of registered general public users). The WegenerNet is an open access public utility, available to serve as a high-resolution monitoring, validation, and model evaluation facility at a midlatitude location with temperate climate but high weather variability and pronounced climate change trends. It aims to support research, education, and applications that can benefit from its long-term observational coverage of the 1–10-km-scale range, which is its core added value.

In this paper we first describe the WegenerNet design and setup, including scientific–technical aspects, but also how we coped with underlying institutional, logistical, and other challenges involved in acquiring and maintaining the 151 long-term station locations. Next we describe the automated processing system and available data products and their provision to users. Following this introduction of the network itself, we discuss its utility by showing some example results, including extreme weather event examples, climate variability over the 5-yr period from 2007 to 2011, and an example of calibration support to coupled climate–hydrology modeling.

TABLE 1. Summary of WegenerNet station and sensor characteristics.

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Stations summary				
Station type	**No. of stations**	**Station No. (1–151)**	**Measurement parameters [sensor height (m)]**	**Temporal resolution (min)**
Base stations (B)	127	All, except numbers of BS, P, R stations	Air temperature (2)	5
			Air relative humidity (2)	5
			Precipitation (1.5)	5
Special base stations (BS)[a]	11	6, 15, 19, 27, 34, 50, 54, 78, 84, 85, 99	+Soil temperature (−0.3)	30
			pF value (−0.3)	30
	1	151	Like B, but no precipitation	5
Primary stations (P)[a]	11	11, 32, 37, 44[b], 72, 74, 82, 101, 132, 135, 139	+Solid[c] precipitation (1.5)*	5
			Wind parameters[d] (10)**	5
Reference station (R)[a]	1	77	+BS, solid[c] precipitation (1.5)	30, 5
			Wind parameters[d] (10)	5
			Air pressure (1.5)	5
	(151 total)		Net radiation (2)	5
Sensors summary				
Sensor description		**Sensor type**	**Detailed information/website**	
Combined sensor for air temperature and relative humidity (B, BS, P, R)		Temperature: PT1000 (1/3DIN) Humidity: Sensirion SHT75	www.geo-precision.com www.sensirion.com	
Precipitation sensor Friedrichs (B, BS, R)		7041.2000, Reed contact, 211 cm^2	www.th-friedrichs.de	
Precipitation sensor Young (P, R)		Model 52202 H 220V, 200 cm^2	www.gwu-group.de	
Precipitation sensor Kroneis (R)		MR3H/Meteoservis, 500 cm^2	www.kroneis.at	
pF value and soil temperature sensor (BS, R)		THT-PT100/SMD, PT1000(SMD)	www.geoprecision.com	
Wind sensor Gill WindSonic (P, R)		WindSonic Option 4 (SDI12)	www.gill.co.uk	
Net radiometer (R)		Type NR Lite/Kipp & Zonen	www.kroneis.at	
Air pressure sensor (R)		Type 315K/Kroneis	www.kroneis.at	

[a] Measurement parameters listed for BS, P, and R are those that are measured in addition to the B parameters.

[b] Station 44 is a silo rooftop station in the Raab valley measuring temperature and relative humidity at a height of 53 m.

[c] "Solid" precipitation denotes stations equipped with heated rain gauges (no heating for B, BS); * height for station 44 is 52 m.

[d] Wind parameters include speed, direction, gust, and gust direction; ** height for stations 44, 72, 101 is 55, 18, 14 m, respectively.

For further and more detailed information, we refer to a recent more technically oriented introduction by Kabas et al. (2011b) and a comprehensive description by Kabas (2012). The latter is a doctoral thesis in German (serving the broad national community), but the main details will also be available soon through upcoming English publications scheduled for spring 2014 (including master of science theses with details on the processing system). The WegenerNet homepage (www.wegcenter.at/wegenernet) provides online information; the data portal (www.wegenernet.org) provides online data access, including visualization and download.

NETWORK DESIGN AND SETUP. While the density of common meteorological networks corresponds to average station distances larger than 10 km [e.g., about 18 km for the network of the Austrian national meteorological service Zentralanstalt für Meteorologie und Geodynamik (ZAMG; Kann et al. 2011)], and while dedicated mesonets such as the Oklahoma Mesonet (McPherson et al. 2007) and the Helsinki Testbed (Koskinen et al. 2011) as well focus on the 10-km scale, there have already been experiments including dense networks down to the 1-km scale (e.g., Wulfmeyer et al. 2008). These experiments have been carried out as part of time-limited campaign studies, however, so that the WegenerNet is the first long-term station grid at these 1-km scales. For such a long-term network, it is particularly important to find a suitable region, fitting both in terms of diverse weather and climate conditions and feasibility of reliable stakeholder partnerships.

Within the constraints that the field infrastructure should be reasonably accessible from Graz (i.e., be located in southeastern Austria) and that it should allow the state level as an institutional umbrella for stakeholders (i.e., be part of the state of Styria), we selected the county of Feldbach in southeast Styria for its diversity and variability of weather and sensitivity to climate change.

This region in the Alpine foreland at the interface between Mediterranean and Alpine climate is characterized by cold winters, hot summers, occasionally strong winter storms, summer precipitation dominated by heavy rain from thunderstorms, and is a European hotspot for hailstorms (Kabas 2012, chapter 1; Harlfinger et al. 2010; Wakonigg 1978). It is also particularly sensitive to changes in climate conditions (e.g., Auer et al. 2001, 2007; Heinrich 2008; Kabas et al. 2011a; Kotlarski et al. 2012). For example, Kabas et al. (2011a) found summer trends in southeastern Styria over 1971–2007 to amount to

$0.71° \pm 0.23°C$ decade^{-1} (95% confidence range), consistent with trends in the larger-scale eastern Alpine foreland region (Auer et al. 2007). On the modeling side, weather prediction and climate projections that use existing mesoscale observations alone face severe challenges because of lacking local-scale information in this meteorologically active region; complementary high-resolution measurements are therefore strongly beneficial (Kann et al. 2011; Prein et al. 2013a).

We invested substantial communications work in 2005 for building all necessary partnerships with the region as well as at the county and state levels, which was indispensable for enabling the feasibility of the WegenerNet project as a long-term endeavor. Fortunately, we received strong interest from key stakeholders in the region, and even substantial funding contributions toward the initial infrastructure. Mayors and councils of the 27 municipalities in the county that are part of the WegenerNet region encouraged and actively supported to acquire stations in their areas—the collective area of the 27 municipalities in fact explaining the somewhat nonrectangular shape of the grid seen in Fig. 1b. Weather-interested companies, farmers concerned about climatic change already ongoing, and individual weather enthusiasts from the region helped to secure nontime-limited written commitments for the 151 station locations. Relevant state departments supported us with all needed planning information, from their geographical information system (GIS) resources as well as their land registry and ownership information.

The technical design is illustrated in Fig. 1b, showing the different station types that we chose. The instrumentation per station and the related sensor information are summarized in Table 1. We numbered the stations row wise throughout the 150 grid cells, starting with the cell in the northwestern corner of the grid (e.g., station 11, numbered in Fig. 1b, is the third station in the second row after eight stations in the first row). The actual selection of station locations in the hilly landscape (see Fig. 1b and its caption), nominally as close as feasible to centers of design grid cells, was a comprehensive work until spring 2006. It involved on the one hand GIS information as illustrated in Figs. 2a,b and on the other hand careful consideration of local station environments, land owner constraints, and climatological representativity for grid cells. The setup of the stations after the selection phase, illustrated in Figs. 2c–h, was another comprehensive undertaking, essentially completed by end of 2006. Again, here the reliable stakeholder partnerships built during the planning phase in 2005

were indispensable for success, since without the substantial support and enthusiasm of local partners, the infrastructure work combined with long-term commitment is not achievable at any reasonable cost for a university-hosted field facility with 151 locations. For further details on station setup, see Kabas (2012, chapter 3).

For budgetary and ease-of-maintenance reasons, we mainly chose base stations (127 stations) that only measure the core parameters of temperature, precipitation, and humidity, and that can automatically operate without an electrical power supply by long-duration batteries. Eleven special base stations were equipped with solar panels for some extra power, for measuring in addition soil temperature and soil moisture (or more precisely, the so-called pF value, from which soil moisture is derived; Van Genuchten 1980). They complement the base station data with

valuable hydrological data at locations representing important soil types of the region [for details see the appendix in Kabas (2012)]. One special base station (station 151) is joining the cell of station 44—which is a silo rooftop station at about 50-m height above the Raab valley for measuring the airflow aloft (see also footnotes in Table 1)—in order to observe temperature and humidity on the valley ground near the silo tower.

The primary stations, clustered over the grid with an average distance of about 5 km, are equipped with an electrical power supply and measure precipitation with heated rain gauges (in winter) as well as measure wind parameters. Three of these stations—44, 72, and 101—do not measure the wind at 10-m masts as illustrated in Figs. 2g,h, but rather higher up as indicated in the footnotes of Table 1, taking advantage of the possibility to mount the mast on silo rooftops. A central reference station (station 77) in addition measures air pressure and net radiation and employs multiple rain gauges.

Operations and maintenance are supported in the field by two
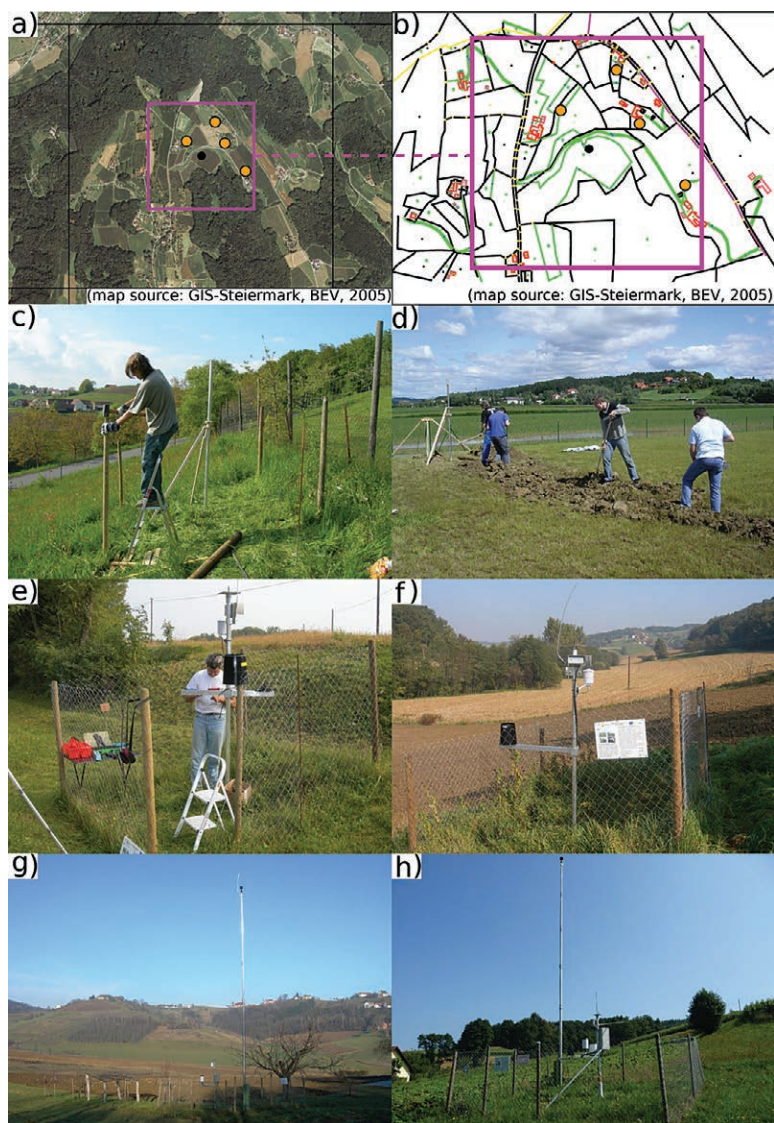
FIG. 2. Design and setup of the WegenerNet stations. A diversity of GIS maps and land registry information, from cooperation with state departments, supported the acquisition of long-term station locations, where (a) shows an aerial photo of land cover for an example grid cell (purple rectangle, center marked with black dot) with a few candidate station locations indicated (orange dots) and (b) shows the candidate locations and is closer into the grid cell, focusing now on land property information (black parcels) as well as street and housing information (black dashed and green lines, reddish symbols). (c),(d) Students from local agricultural colleges and land owners help with setting up basic station infrastructure. (e) The instrumentation is mounted by a professional weather station engineer. (f) View of a base station, which occupies a nominal area of about 9 m²; special base stations use the same area. (g) View of a primary station, and (h) view of the reference station, both station types using an area of about 25 m² and both views showing also the mast with the wind sensor 10 m above ground.

permanent "station guards" living in the region, knowing it intimately, and solving any routine maintenance tasks (taking care of the station infrastructure and maintaining good relations with land owners, mowing grass, changing batteries, handling small emergencies, such as blocked rain gauges, etc.). Their work is coordinated by an engineer of our team at the Wegener Center who is in charge of the field operations. The operations are based on a dedicated operations and maintenance guide and are supported by web-based tools that we developed to show the operation status of all stations and to log maintenance activities (Kabas 2012, chapter 3). These tools enable swift action in case of any anomalies in status parameters, and are supported by aids such as automatic daily status-alert e-mails to the engineer in charge of field operations and the engineer in charge of the processing system. The latter two are the core operations team, assisted by the two station guards; thus clearly a high degree of automation is needed to run the WegenerNet smoothly by this highly efficient yet small core team.

WEGENERNET PROCESSING SYSTEM AND DATA PRODUCTS.

The acquisition of the data from the station grid, their processing by the WegenerNet Processing System (WPS), and the presentation of data products to users via the data portal are shown at an overall structure level in Fig. 3. The WPS is the core system in this context. Table 2 summarizes scientific–technical details of the data levels involved and of the main processing steps, from receiving and archiving the raw data via quality control and data product generation to weather and climate products ready for the data portal. The WPS is a fairly comprehensive system, from years of development from fall 2006 to present, but we confine ourselves to a reasonably brief introduction here in order not to overwhelm with technical details. Interested readers are referred for more information on the WPS to Kabas et al. (2011b) and Kabas (2012, chapter 4).

The WPS consists, as Table 2 indicates, of four main software subsystems: the Command Receive Archiving System (CRAS), archiving level 0 raw data; the Quality Control System (QCS), supplying level 1 quality-controlled data; the Data Product Generator (DPG), yielding station time series and gridded level 2 data products; and the Value-Added Products System (VAPS), providing level 2+ derived data products computed from the level 2 data of directly measured parameters. The WPS data are linked to the Visualization and Information System (VIS), which offers the data to users via the WegenerNet data portal (www.wegenernet.org).

Except for the basic logger and general packet radio service (GPRS) transmission control software of the CRAS, which is mainly using web-based tools by the logger supplier GeoPrecision GmbH, Germany, we developed the WPS throughout in the flexible scripting language Python, with the database (PostgreSQL) and auxiliary
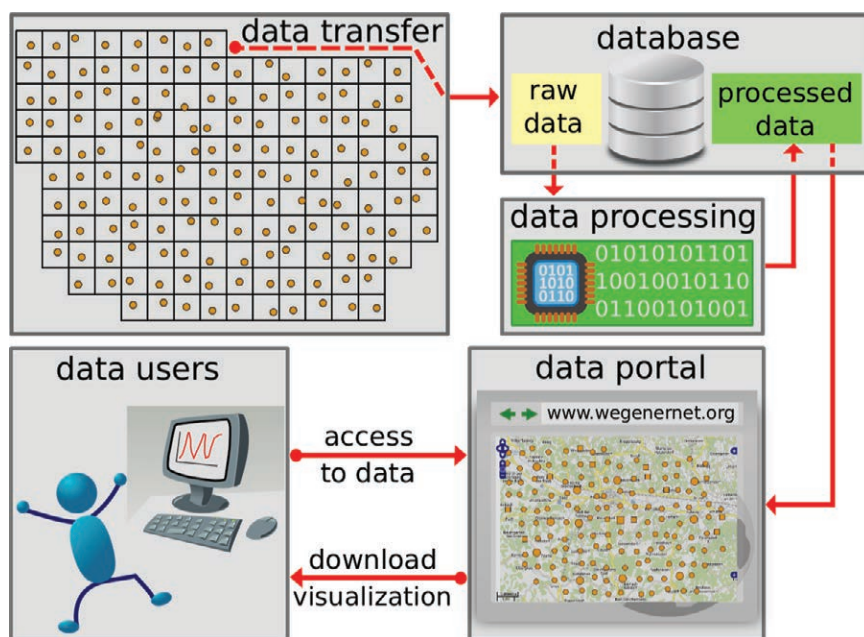
Fig. 3. Schematic view of the WPS. The 151 stations in the field are equipped with Internet loggers and global system for mobile communications (GSM) devices and antennas (i-Log-3V or i-Log-12V loggers of GeoPrecision GmbH, Germany; www.geoprecision.com). The raw data are transferred via GPRS transmission to the database at the Wegener Center Graz. There they are automatically processed by the WPS to quality-controlled station time series and (200 m × 200 m) gridded fields, with time resolution from basic 5-min data to seasonal and annual mean data. The data are available to users via the WegenerNet data portal in near–real time (1–2-h latency) for visualization and download.

WPS flow	Description of WPS flow	Main processing steps	Description of data levels and processing steps
			Table 2. WPS data levels, processing subsystems, and main processing steps.
Raw data	Sensor measurements		(measured parameters per station according to Table 1)
L0P: CRAS	Level 0 processor: Command Receive Archiving System	Logger and sensors command and control	Global Platform Shell (GPShell) software package and user interface tools by GeoPrecision GmbH, Germany
		Logger data reception and XML conversion	Two scripts by GeoPrecision GmbH adapted for the WegenerNet, especially for providing XML raw files
		Database ingestion of level 0 sensor data	Program [hypertext preprocessor (PHP) script] accessing XML raw files and feeding the WegenerNet PostgreSQL database
L0 data	Database-archived data		(sensor data at native 5-min/30-min time resolution, complemented by all needed meta information)
L1P: QCS	Level 1 processor: Quality Control System (QC layers 0–7: qcl-0 to qcl-7)	qcl-0: check regarding station operation	Check if station is currently in operations (if not, set the QC flag to 1 and skip qcl-1 to qcl-7 for the station)
		qcl-1: check of data availability	Check if expected sensor data values are available (if not, add 2 to the QC flag and skip qcl-2 to qcl-7)
		qcl-2: check of sensor functioning	Check if measurement value exceeds permitted range of technology sensor specifications (if yes, flag +4)
		qcl-3: check of climatological plausibility	Check if measurement value exceeds plausibly set maximum climatological bounds (if yes, flag +8)
		qcl-4: check of temporal variability	Check if measurement value shows too high or too little change ("jumps," "constancy") (if yes, flag +16)
		qcl-5: check of intrastation consistency	Check if measurement value is not properly consistent with related parameters (if yes, flag +32)
		qcl-6: check of interstation consistency	Check if measurement value deviates too much from values at neighbor stations (if yes, flag +64)
		qcl-7: check against external reference	Check (for pressure) if measurement value deviates too much from ZAMG reference (if yes, flag +128)
L1 data	Quality-controlled data		(quality-flagged time series data of all parameters; flag-0 data used by the DPG for product generation)
L2P: DPG	Level 2 proces-sor: Data Products Generator	Station time series generation (basis data)	Time interpolation, "missing value" assignment, neighbor- and grid-based interpolation, as needed
		Gridded-fields generation (basis data)	Inverse-distance weighted interpolation of temperature, precipitation, humidity to grids; temperature also terrain following
		Weather data products generation	Averaging of basis data (summation for precipitation) to half-hourly, hourly, and daily data products
		Climate data products generation	Averaging of weather data (summation for precipitation) to monthly, seasonal, and annual climate data
L2 data	Weather and climate data products		(5-min/30-min basis data; half-hourly, hourly, daily, monthly, seasonal, and annual time series data of all parameters; gridded fields of temperature, precipitation, humidity)
L2+P: VAPS	Level 2+ processor: Value-Added Products System	Soil moisture time series generation	Derivation of soil moisture data products from level 2 pF value data and auxiliary soil-related metadata
		Proxy-station time series generation	Derivation of temperature, precipitation, humidity time series from level 2 grids at user-defined proxy-station locations
		Heat index field generation	Derivation of heat index data products from level 2 temp and humidity grids (including comfort-level information)
L2+ data	Value-added data products		(time series data of soil moisture and for proxy stations; gridded fields of heat index)
VIS	Visualization and Information System		WPS data to users via the WegenerNet data portal
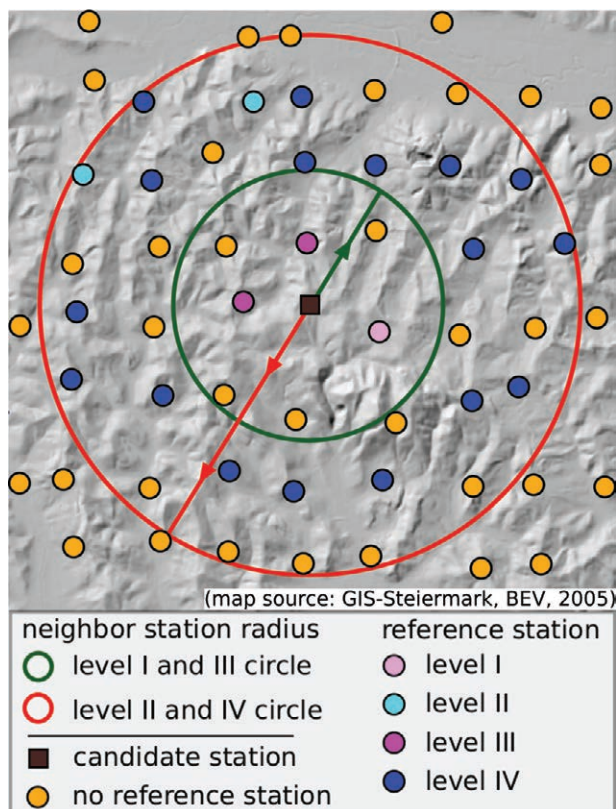
Fig. 4. Scheme for interstation consistency check as part of the WPS QCS. In this check each station is monitored as a candidate station (middle), the measurements of which (such as temperature, precipitation) are intercompared to suitable neighbor stations with comparable properties serving as reference (e.g., similar altitude, land class). Implausible values, such as from a blocked rain gauge receiving no precipitation while stations around receive some, are flagged.

utilities (e.g., netCDF for the gridded data files) also being open source products. We followed the same approach for the VIS, where we used the scripting language PHP and open source GIS utilities such as MapServer, OpenLayers, and OpenStreetMap. This ensures a high degree of commercial independence and cost effectiveness, which we found to be crucial ingredients for professional yet low-cost, long-term operations in a university environment.

Turning our attention to the subsystems, the first one is CRAS. The CRAS controls the raw data acquisition by the Internet loggers and ingests the level 0 data into the database at the WegenerNet servers in Graz. The GPRS transmission is done hourly, with subsets of about 15 stations transferring in stacked 3-min batches during the first half of the hour, which was found to be important for a smooth and low load to the mobile network at all times. Data from stations failing to transfer nominally (e.g., because

of a temporary local failure to establish mobile connection) are transmitted with the next successful transfer, usually the hour after (logger storage would, in principle, allow a couple of months of backlog). Experience shows that the data transmission is reliable; generally more than 92% of all data are transferred at first instance. The database archives the level 0 sensor data as well as auxiliary information, such as housekeeping data (e.g., logger health parameters). It also is filled, and updated as needed, with meta information for all stations (coordinates, local geographic and environmental characteristics, maintenance information, etc.), which is required with the sensor data for the subsequent processing.

The QCS is run hourly, after the hourly level 0 data ingestion by the CRAS is completed, and it checks for each of the 151 stations the availability and the technical and physical plausibility of the measured data in eight quality-control (QC) layers (0–7) as summarized in Table 2. If the QC layers 0 and 1 find a station and sensor to be currently in operations (so that further checks make sense), then the layers 2–7 have to be passed without violating any QC criterion in order that a level 1 data value receives a QC flag 0 (= ok) status. Otherwise, any nonzero quality flags of QC layers n add up to a number from 1 to 255 that uniquely identifies the alerting layers (8 bit 2^n flagging system; Kabas et al. 2011b).

As seen in Table 2, QC layers 2–5 and 7 are fairly common types of checks, on bounds and deviations, which nevertheless demanded detailed study to define reasonable specifications for the given field region and continue to be subject to further improvement. The interstation check of QC layer 6, which is made to detect implausible "jumps" of parameter values in space, is unique to this type of dense station grid and therefore is separately illustrated in Fig. 4 (for details see Kabas 2012, chapter 4). We save all level 1 data values together with their associated flag in the database. In this way the data can well serve both, further improvement and refinement of the QCS and subsequent derivation of level 2 data products only from level 1 data of flag-0 quality.

Over the five years of 2007–11, more than 95% of the data of active sensors were marked with flag 0. Stations and their sensors themselves also featured high availability, which is illustrated in Fig. 5 for temperature, precipitation, wind, and soil measurements. Together, these quality and availability characteristics indicate the reliability of the network operations. With the relative humidity sensor, there was one sensor type, though, that suffered degradation over the years, with about half of the stations

delivering no flag-0 quality (from dust contamination of the sensor's active area; Kabas 2012). New humidity sensors protected by sinter filters have therefore replaced degraded sensors at reference, primary, and special base stations; replacement at base stations will follow in 2014.

The DPG starts with flag-0 level 1 data and first generates continuous station time series at the basic 5-min time resolution (30 min for soil parameters, see Table 1). We perform linear interpolation over sufficiently short time gaps or otherwise fill in a predefined "missing data" value, each way marked with a distinct nonzero flag. For the main parameters measured over the full grid (temperature, precipitation, humidity), we then proceed to fill gaps with missing data values by spatial interpolation from neighbor stations (the neighbors are selected similarly to the QC interstation check shown in Fig. 4). Subsequently, we construct 200 m × 200 m gridded fields for the main parameters by inverse-distance weighted interpolation from the neighbor stations of any target gridpoint location (inverse-distance-squared weighting for precipitation). For temperature, we produce terrain-following fields and a field at a representative reference altitude of 300 m. Finally, we use the fields to spatially interpolate back from neighbor grid points to station locations where missing data values still remained; such grid-based interpolation values are marked with a further nonzero flag.

The output of the DPG are the level 2 weather and climate data products summarized in Table 2, which in addition to the data at native (5 min/30 min) resolution include time averages, or summations over time in the case of precipitation, ranging from half hourly to annual (for details see Kabas 2012, appendix B). The VAPS is a system attached to the DPG, using its level 2 data to generate derived products. These level 2+ data currently include soil moisture time series derived from the pF value measurements (reprocessing was completed by mid-2013), proxy-station time series at user-defined locations interpolated from temperature, precipitation, and humidity fields, and heat index fields (and associated comfort-level classes) derived from temperature and humidity fields (using the recent formulas of Schoen 2005).

Using the WPS data, the VIS interfaces them to users via the WegenerNet data portal (www.wegenernet.org), whereby the level 2/2+ data are made available to external users (to internal team users, also level 0/1 data). After a simple registration process, the portal provides convenient online access, and visualization and download capabilities.

Its design is bilingual (German, English) to effectively serve both national and international communities, and its integrated help information (data portal guide, data fact sheet, etc.) should make its use straightforward without separate explanation.

EXAMPLE RESULTS—UTILITY FOR WEATHER AND CLIMATE. We start with examples of extreme events: one, a strong storm in winter (Fig. 6); the other, a heavy precipitation event in summer (Fig. 7). These examples serve to illustrate the utility of the network to observe weather events at a 1-km scale/5-min resolution; it is not the purpose to discuss the meteorological case of the events in detail.

Winter storms associated with the midlatitude cyclones Paula and Quitta on 26–28 January 2008 brought considerable storm damage to Europe
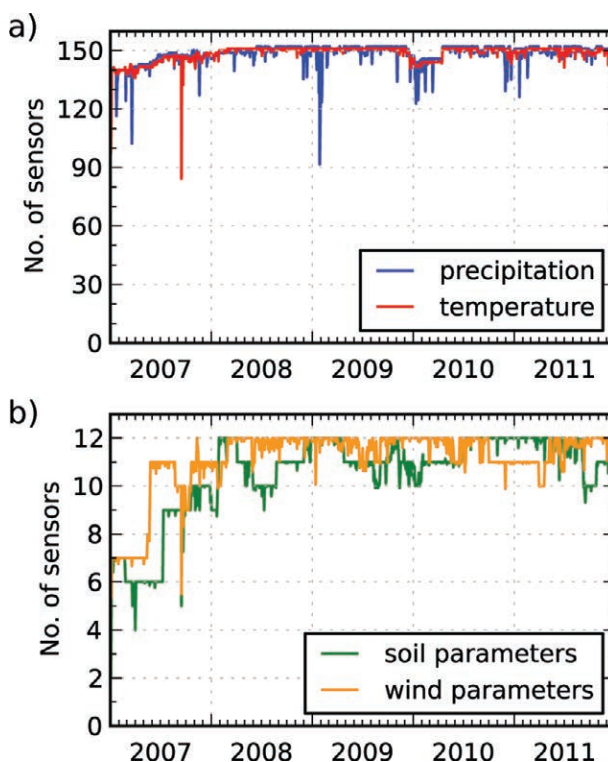
FIG. 5. Data availability statistics over the 5-yr period from 2007 to 2011, showing the number of sensors (stations) producing data that pass quality control (flag-0 data). (a) Temperature and precipitation are measured at all 151 stations and generally more than 95% of the stations deliver flag-0 data. Exception is precipitation during winter; since base station rain gauges are not heated, some fail during cold periods (blue spikes). (b) Wind and soil parameters are measured at the 11 primary stations and the reference station; since having finalized the instrumentation of these stations during the initial year 2007, generally at least 10 or 11 stations deliver flag-0 data.
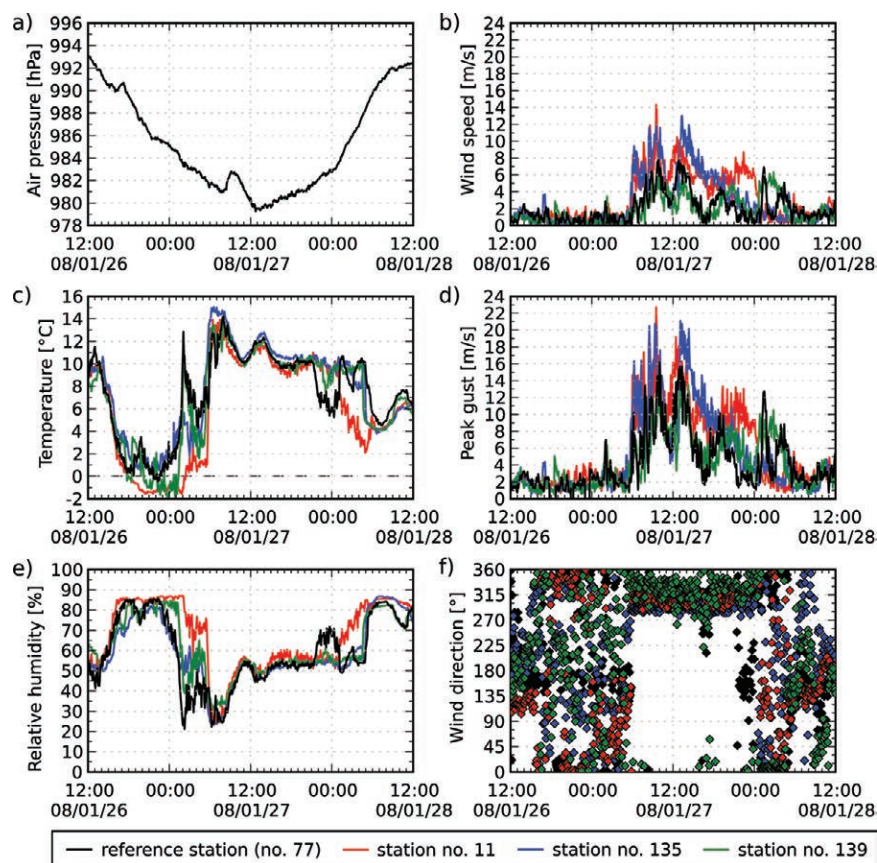
FIG. 6. Time series observations of meteorological conditions before and during the midlatitude cyclone Quitta on 27–28 Jan 2008 at four different WegenerNet stations. These span the region from northwest (station 11, red) via center (station 77, black, air pressure only from this station) to south (station 135, blue) and southeast (station 139, green) (see the locations in Fig. 1). Peak gusts higher than 20 m s^{-1} were reached, and the highly variable local conditions captured by the dense station network during the night of 26–27 Jan 2008 were stratified by the northwesterly inflow of the storm's air mass (from directions around 315°) starting at about 0530 UTC. After this onset temperature, humidity and wind direction across the region are strongly constrained by this air mass.

and on 27 January especially also to southeastern Austria (Axer et al. 2009; Pfurtscheller 2009). The WegenerNet region was near the southern margin of strong storminess. The associated meteorological conditions are illustrated in Fig. 6 based on selected station time series at 5-min resolution.

This type of view enables quantitatively inspecting at the same time local-scale differences during pre-storm conditions, related to orography and local time, and large-scale airflow dominance during storm conditions. For example, within the last hours before the storm (from about 0200 to 0530 UTC), temperatures between the northeastern Raab valley (station 11) and the central reference station (station 77) at very similar altitude deviated by about 5°–12°C, while during the main storm phase all stations experienced the same warm airflow and exhibited deviations within about 1°–2°C only (Fig. 6c). This type of case study data are also valuable to test high-resolution weather models for how well they capture local orographic and diurnal cycle effects. It is, furthermore, valuable for educational purposes: teachers and pupils from high schools in the Feldbach region and elsewhere, for example, use station data intercomparison directly based on the data portal for simple yet effective hands-on learning about meteorological conditions associated with severe weather events such as windstorms and flooding.

On 4 July 2009 after noontime, strong convective precipitation cells crossed the WegenerNet region. Figure 7 illustrates the related temperature and precipitation observations in the form of a sequence of 5-min snapshot data of the 200 m × 200 m gridded fields, spanning the 22 km × 15 km total area of the level 2 field products. For temperature the terrain-following fields are shown, clearly depicting also the influence of the orography. For the precipitation fields, it has to be kept in mind that at the subhourly time scales inspected here, the actual precipitation patterns may exhibit still more spatial variation than resolved by the dense station grid—that is, the spatial correlation of such 5-min rainfall snapshots can be smaller than the station distances. The 200 m × 200 m gridded fields at these short time scales may therefore contain smoothed representations of actual patterns, while hourly or longer averages will lead to sufficient correlation from pattern movements and hence to well-representative gridded fields.

In any case this type of gridded-fields view highlights the resolving power of the full station grid, which is especially useful for precipitation case studies—for

example, for validating and calibrating concurrent precipitation radar data over the region or for testing differences in area-integrated heavy precipitation estimates over small catchment areas between such fine-resolved data and standard station networks with station distance scales >10 km. Regarding the latter, an analysis by Kabas (2012) of another heavy precipitation event on 23–24 June 2009 (not shown) indicated the capacity of the WegenerNet to capture the extreme precipitation, while the two national meteorological stations ("ZAMG stations" in Fig. 1) could not sufficiently capture it because the most heavy rain loads had occurred north of the river Raab (and had led to severe flooding, especially in the northeastern part of the region).

Figures 8 and 9 show examples of climatological temperature data and of precipitation data, respectively, in the form of exemplary monthly and seasonal gridded fields (Figs. 8a,b, 9a,b) and in terms of statistics and time series over the five years from 2007 to 2011 (Figs. 8c,d, 9c,d). This serves to illustrate the utility of the network to characterize local-scale climate, including orographic influences, and the level of consistency of long-term (multiyear) measurements with external quality data sources. As for the weather events mentioned above, it is not the purpose to discuss specific climatological aspects in detail (also, the data record is still short, so that we cannot yet obtain climatologies in a classical sense, which would need time periods of typically at least 20–30 years).

The monthly-mean temperature field in Fig. 8a indicates a moderate urban heat island effect for the cities of Feldbach (center)

and Bad Gleichenberg (south). The 1300–1400 LT monthly mean in Fig. 8b clearly shows the topography, with the Raab valley being warmest. Figure 8b is an example of the local-time-resolved climate data products: in addition to monthly, seasonal, and annual mean fields from full days, level 2 climate fields are also available for each of the individual 24 hours of the day. This is, for instance, useful for statistical testing of the diurnal cycle performance of weather and climate models at local-scale resolution. Kann et al. (2011), who used four years of WegenerNet
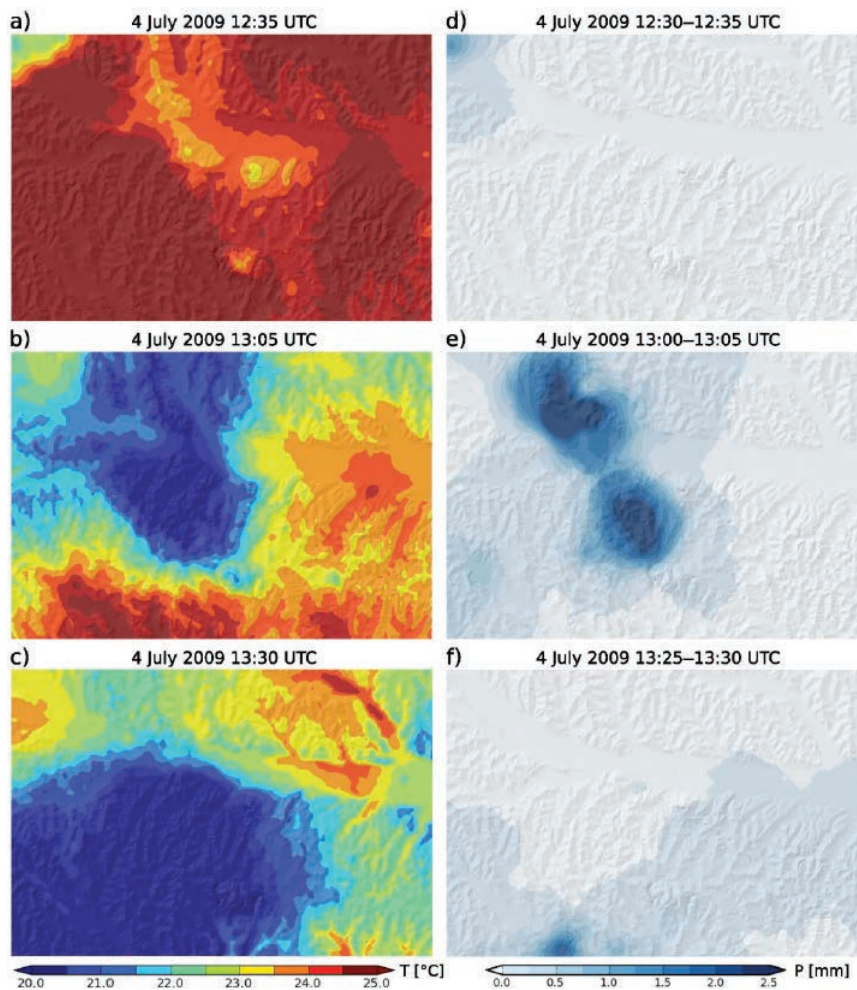
FIG. 7. Gridded field observations of (left) temperature and (right) precipitation patterns over the WegenerNet region, during a strong convective precipitation event on 4 Jul 2009 after noontime. (from top to bottom) Three snapshots of 5-min data at three times separated by about half an hour are shown. As of about 1230 UTC on this hot summer day, the very northwestern part of the region shows (a) cooling from the (d) first precipitation cell coming in. Around 1300 UTC, distinct precipitation cells drop heavy rain at a rate of more than 3 mm per 5 min on (e) a substantial part of the region, with (b) the southern part still being dry and partly warmer than 25°C. Around 1330 UTC (f) the strong rain is over and has left substantial cooling except for the northeast, which had received no substantial rain and has already recovered to warmer than 25°C (c) in a northeastern side valley.
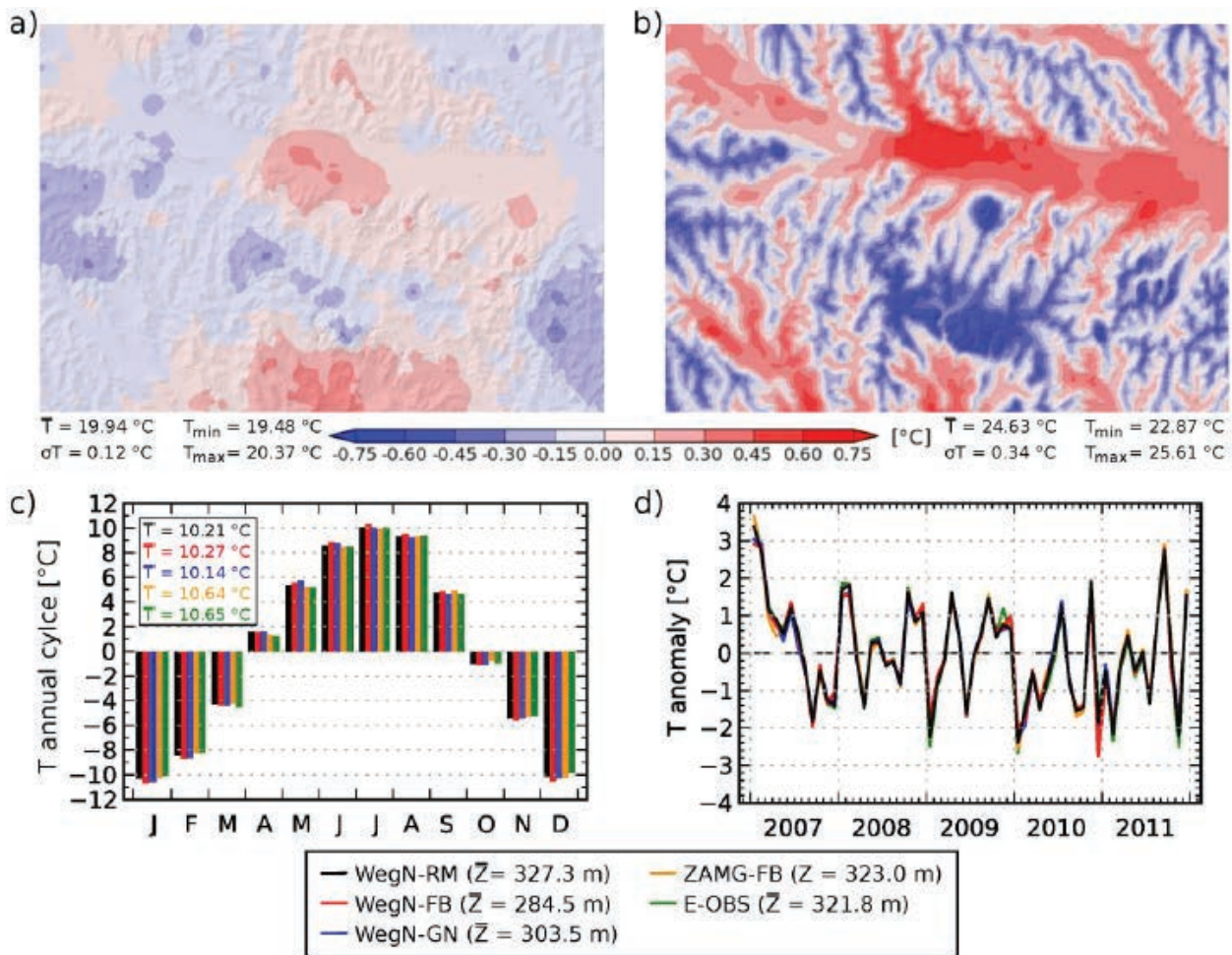
FIG. 8. Illustration of climatological temperature data from the WegenerNet. (a) Monthly-mean temperature field and (b) monthly-mean temperature field after noontime (1300–1400 LT data) for Jul 2008. The legend shows the region-mean value ($\bar{T}$), the minimum/maximum mean value of all gridpoint locations (T_{min}/T_{max}), and the standard deviation of the gridpoint means against the region mean (σT). (c) Mean annual cycle of monthly-mean temperatures from the period 2007–11, and (d) monthly-mean temperature anomaly time series (i.e., mean annual cycle subtracted), for the WegenerNet region-mean data (WegN-RM), Feldbach-subregion-mean data (WegN-FB, includes stations 45, 46), Gnas-subregion-mean data (WegN-GN, includes stations 115, 116, 129, 130), ZAMG Feldbach station data (ZAMG-FB), and E-OBS selected-region-mean data (E-OBS); see Fig. 1 for the station locations and the E-OBS region. Five-year-mean values of the datasets [legend in (c)] and mean elevations of the stations (legend at bottom) are shown as well.

temperature, humidity, and wind data for statistical validation of Austrian high-resolution empirical analyses constructed from data at >10-km resolution scale (Haiden et al. 2011), found high value also for such analysis validation. As Figs. 8c,d show, the WegenerNet temperature data are highly consistent internally among stations as well as compared to established external data sources.

For the seasonal precipitation shown in Figs. 9a,b, it is visible that during the summer season, dominated by convective precipitation events in this region, total precipitation can vary by more than 30% between locations, even at the small spatial scales

of the WegenerNet region. Figures 9c,d indicate that the WegenerNet precipitation data are overall consistent internally between rain gauge types and compared with external data sources; however, individual seasonal sums can be uncertain to several 10% uncertainty. The precipitation data, therefore, deserve further characterization in order to improve their long-term utility. This is part of ongoing work that at the same time is an excellent example for the integration of WegenerNet analyses in university education: students in summer internships have scrutinized precipitation datasets for weaknesses as part of advancing their practical meteorological skills, and
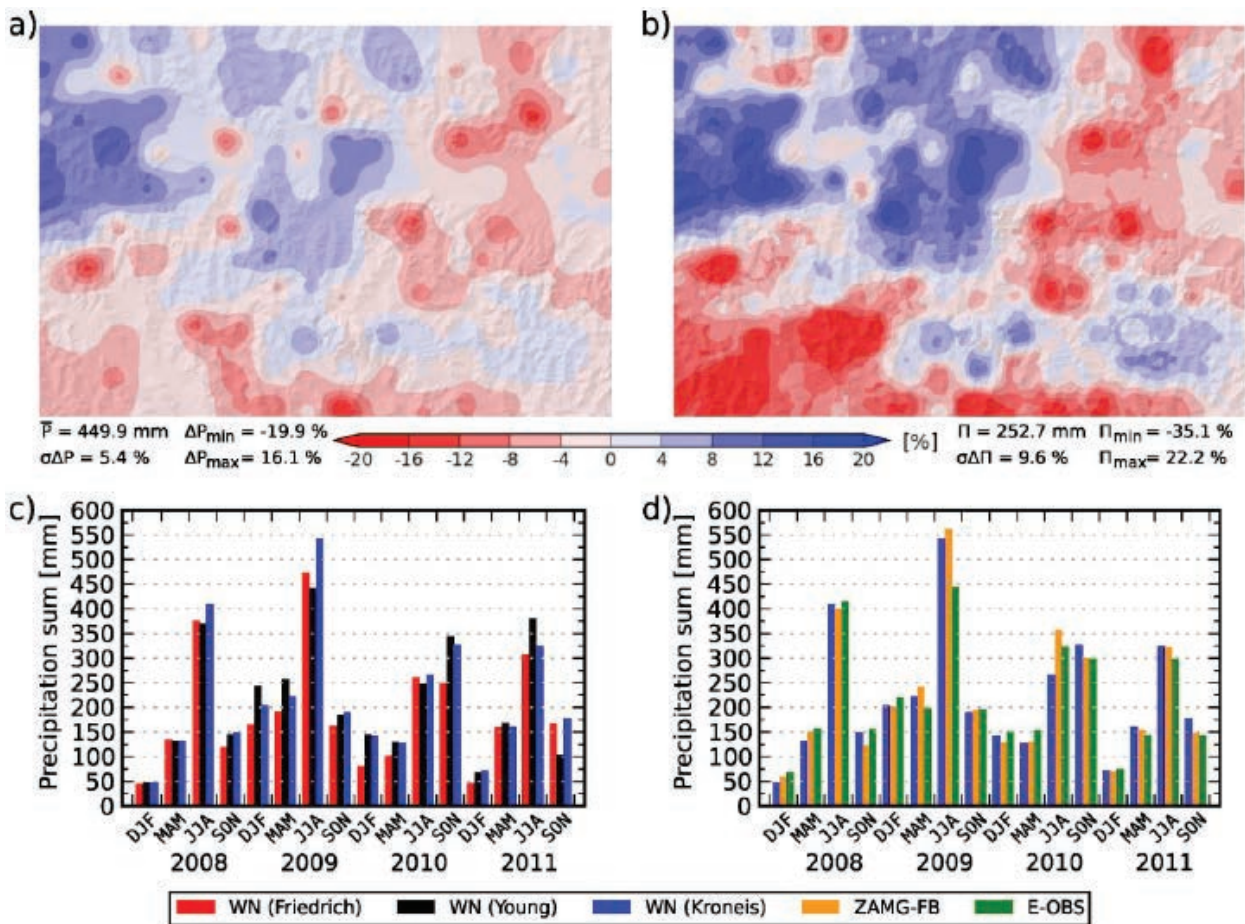
Fıg. 9. Illustration of seasonal precipitation data from the WegenerNet. (a) Seasonal-sum precipitation field and (b) seasonal-sum precipitation field for heavy precipitation (hours with >4 mm h⁻¹ rain rate only) for Jun–Aug (JJA) 2009, with the legend showing also the region-mean sum ($\overline{P}$, $\overline{\Pi}$), the minimum/maximum deviation of all gridpoint locations relative to the region mean ($\Delta P_{min}/\Delta P_{max}$, $\Delta\Pi_{min}/\Delta\Pi_{max}$), and the relative standard deviation of the gridpoint values against the region mean ($\sigma\Delta P$, $\sigma\Delta\Pi$). (c),(d) Seasonal precipitation sums from Dec to Feb (DJF) 2007/08 to Sep to Nov (SON) 2011, for the WegenerNet Friedrichs-type rain gauges (WN Friedrich, average over 139 base/special base stations), Young-type gauges (WN Young, average over 11 primary stations), Kroneis-type gauge (WN Kroneis, station 77 only), ZAMG Feldbach station gauge (ZAMG-FB), and E-OBS selected-region average data (E-OBS, average); see Fig. 1 for station locations and types and for the E-OBS region.

graduate students then took over for detailed analysis and improvement of aspects of quality control and data product generation. In the field we recently implemented, as a systematic precipitation infrastructure update during fall 2013 for the long-term, a replacement of the ~200 cm² gauges at all primary stations (Young gauges; see Table 1) with 500 cm² (Kroneis) gauges.

Figure 10 illustrates an example application of WegenerNet data in a coupled climate–hydrology modeling study in the region (Reszler et al. 2011). Temperature and precipitation fields were used at 1 km × 1 km resolution to correct data from the Consortium for Small-Scale Modeling (COSMO) model in climate mode (CCLM; Böhm et al. 2006)

before they were fed into the hydrological modeling system MIKE SHE (Refsgaard and Storm 1995). The WegenerNet data helped to significantly improve the estimation of monthly specific runoff over 2007 at the water gauge used for hydrologic validation (Fig. 10b). This example serves to indicate the utility of the WegenerNet to support validation, calibration, and improvement of models. At the meteorology–hydrology interface, the soil moisture data are also very valuable, since soil moisture is often prognostic in both the land surface schemes of meteorological models and hydrological models.

SUMMARY AND PROSPECTS. In 2005 we started to implement the WegenerNet as a pioneering
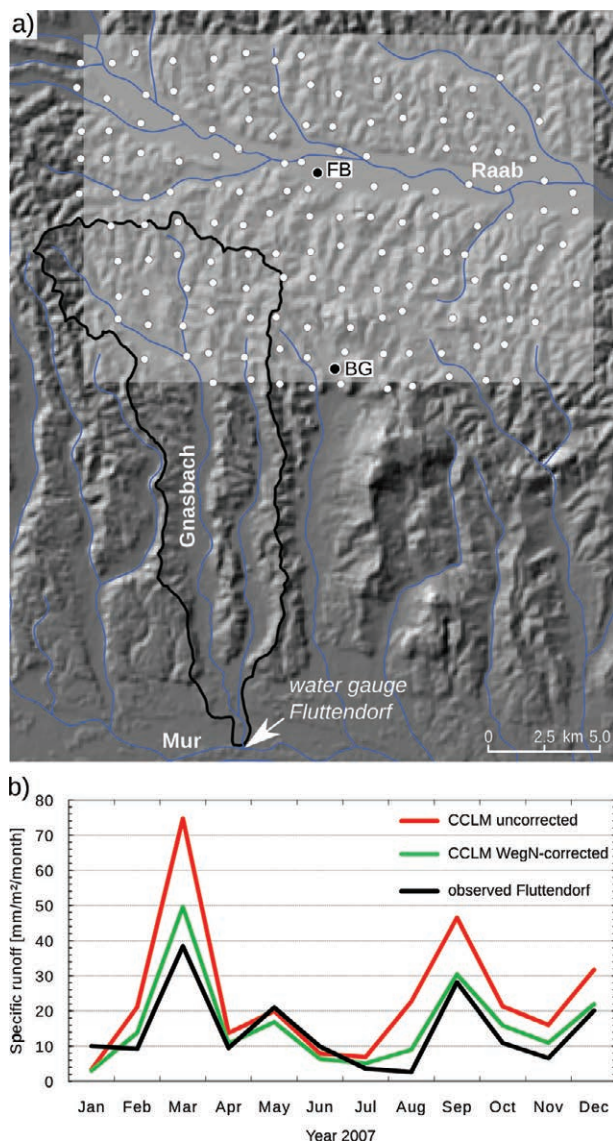
Fig. 10. Application of WegenerNet data in a coupled climate–hydrology modeling framework. (a) The Gnasbach catchment area (bold-bordered area), partially covered by the WegenerNet region in the north (gray area with station symbols) and ending with the water gauge Fluttendorf in the south (Gnasbach joining into river Mur). (b) Monthly specific runoff of the Gnasbach over the year 2007 as observed at gauge Fluttendorf (black), simulated by hydrological modeling using input meteorological data from the model CCLM in uncorrected form (red) or bias corrected by WegenerNet observations (green). The WegenerNet data have been effective to mitigate precipitation (temperature) overestimation (underestimation) by the CCLM, which enabled improved hydrological model input and consequently improved runoff estimation.

meteorological station network at 1-km-scale resolution in the Alpine foreland of southeast Austria in the region of Feldbach. Since 2007 the 151 stations of the tightly spaced grid in an area of about 20 km × 15 km provide regular measurements, are processed to a variety of useful weather and climate data products, and are available via a data portal (www.wegenernet.org).

Ongoing and future work will further maintain and improve the infrastructure (e.g., further replacement of humidity sensors, further modernization and regular calibration of rain gauges), the processing system and data portal (e.g., quality-control procedures, further value-added products), and the verification and validation (e.g., systematic interstation comparison under homogeneous spatial conditions, long-term and case study comparison to best-quality external data for the measured parameters). The several years of operation so far have underscored the importance of continuous efforts on maintenance and improvement as an essential part of managing the network. Only such a proactive approach makes it possible to keep degradation at bay and to sustain and advance the quality of infrastructure and data.

We also will foster joint use of data with partner networks such as the European lightning network LiNet (Betz et al. 2004), for which we host a dedicated station in the region (see Fig. 1) and in Graz, and the International Soil Moisture Network (ISMN; Dorigo et al. 2011), which we joined with the WegenerNet as of 2013. Furthermore, we joined the European Long-Term Ecocystem Research (LTER-Europe) network initiative of long-term field sites (Mirtl et al. 2010) and we started to add to the WegenerNet in Feldbach a complementary small network in the mountainous upper Styrian region of National Park Gesäuse as part of the cooperation platform John's creek valley (Strasser et al. 2013). This complementary network consists of seven mountain-proof meteorological stations within a spatial scale of about 10 km, ranging from valley altitudes below 900 m to mountaintops higher than 2100 m; also these data will be made available via the WegenerNet data portal by fall 2014. This adds strong value for supporting mountain region studies.

In summary we see a decent perspective for the WegenerNet to continue serving interested users with long-term monitoring, validation, and model evaluation data for research, education, and other applications that can benefit from sustained observational coverage of the 1–10-km-scale range.

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