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The Austrian radiation monitoring network ARAD – best practice and added value

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Abstract

The Austrian RADiation monitoring network (ARAD) has been established to advance the national climate monitoring and to support satellite retrieval, atmospheric modelling and solar energy techniques development. Measurements cover the downwelling solar

- and thermal infrared radiation using instruments according to Baseline Surface Radiation Network (BSRN) standards. A unique feature of ARAD is its vertical dimension of five stations, covering an air column between about 200 ma.s.l. (Vienna) and 3100 ma.s.l. (BSRN site Sonnblick). The paper outlines the aims and scopes of ARAD, its measurement and calibration standards, methods, strategies and station locations.
- ARAD network operation uses innovative data processing for quality assurance and quality control, applying manual and automated control algorithms. A combined uncertainty estimate for the broadband shortwave radiation fluxes at all five ARAD stations indicates that accuracies range from 1.5 to 23%. If a directional response error of the pyranometers and the temperature response of the instruments and the data acqui-
- ¹⁵ sition system (DAQ) is corrected, this expanded uncertainty reduces to 1.4 to 5.2 %. Thus, for large signals (global: 1000 W m⁻², diffuse: 500 W m⁻²) BSRN target accuracies are met or closely met for 70 % of valid measurements at the ARAD stations after this correction. For small signals (50 W m⁻²), the targets are not achieved as a result of uncertainties associated with the DAQ or the instrument sensitivities. Additional ac-
- ²⁰ curacy gains can be achieved in future by additional measurements and corrections. However, for the measurement of direct solar radiation improved instrument accuracy is needed. ARAD could serve as a powerful example for establishing state-of-the-art radiation monitoring at the national level with a multiple-purpose approach. Instrumentation, guidelines and tools (such as the data quality control) developed within ARAD
- ²⁵ are best practices which could be adopted in other regions, thus saving high development costs.



1 Introduction

Radiative processes are key for both the natural and the anthropogenic dimension of the climate system as well as its changes. Firstly, the Earth's radiation budget plays an essential role in determining the thermal state of the land surface, the atmosphere, and

- the oceans, thereby also strongly influencing the circulation of the latter two (Ohmura et al., 1989; Ramanathan, 1987). Secondly, the main anthropogenic influence on climate arises through modification of the Earth's radiation budget components (Intergovernmental Panel on Climate Change, 2014). Worldwide in-situ ground and space-based measurements of radiative fluxes are thus performed to (a) improve the process measurements of the summary of the sectors of the s
- ¹⁰ understanding of the present climate system (e.g. Wild et al., 2015), (b) provide validation and calibration data for weather and climate models in order to understand processes in the past and future and/or to improve weather forecasts (Chevallier and Morcrette, 2000; Haiden and Trentmann, 2015; Wild et al., 2001), and (c) support solar energy applications (e.g. Gueymard, 2014).
- ¹⁵ Surface observations have the lowest degree of uncertainty and are therefore used to validate satellite measurements (Gupta et al., 2004). The most prominent, worldwide observational ground-based network for surface radiation fluxes is the Baseline Surface Radiation Network (BSRN), established in the early 1990s (Ohmura et al., 1998) by the World Climate Research Programme (WCRP). BSRN provides measureused with high generative and high temperature between with high several block temperature between the field temperature block.
- ²⁰ ments with high accuracy and high temporal resolution, comprising currently 54 sites in different climate regimes of the world (König-Langlo et al., 2013). Another worldwide network providing surface radiation fluxes is the Global Energy Balance Archive (GEBA) (Ohmura et al., 1989).

Besides these global observational networks, national surface radiation monitoring ²⁵ networks exist such as SURFRAD in the US (Augustine et al., 2000) or SACRaM in Switzerland (Wacker et al., 2011) providing long-term observations for climate monitoring and aiding process level understanding on regional scales such as e.g. the European Alps.



The European Alpine region is known to react especially sensitive to both observed (Auer et al., 2007) and projected (Gobiet et al., 2014) global climate change. The great need and the added-value of long-term measurements of the radiative fluxes in Europe and in the Alps to better understand the drivers of observed and projected changes has
⁵ been widely documented (e.g. Kotlarski et al., 2015; Marty et al., 2002; Philipona, 2013; Wild, 2009). Moreover, state-of-the-art regional climate models still show significant biases considerably adding to the uncertainty of future climate change projections (e.g. Frei, 2003; Haslinger et al., 2013). This ultimately shows the need for a dense network of high precision surface observations of the radiative fluxes especially in complex, densely populated alpine topography and adjacent lowlands, where possible impacts of climate change lead to great vulnerability and accurate estimates of the solar energy resources are needed due to the growing demand for renewable energies.

Large parts of the European Alps are within the national territory of Austria, and are also part of the Greater Alpine Region (GAR) with a unique and outstanding long-term instrumental climatological record (Auer et al., 2007). Significant Austrian contributions

- Instrumental climatological record (Auer et al., 2007). Significant Austrian contributions to the field of solar radiation and albedo measurements and respective developments of instrumentation date back to the 1950s and 1970s (e.g. Dirmhirn, 1951, 1957; Dirmhirn and Eaton, 1975; Dirmhirn and Trojer, 1955; Sauberer and Dirmhirn, 1952). In the meantime the standard meteorological station network of the Austrian Central Institute
- for Meteorology and Geodynamics (ZAMG), which includes the measurement of global horizontal irradiance using a Schenk star pyranometer, began to evolve from 20 stations in 1980 to 235 stations in 2015, the latter corresponding to a mean horizontal station distance of about 20 km. In the 1970s and 1980s, surface radiation studies in Austria were focused on establishing radiation climatologies and increasing the process
- ²⁵ understanding based on the available station data (e.g. Neuwirth, 1980, 1983). From the mid-1990s until today, work related to UV radiation and health risk (e.g. Blumthaler et al., 1996; Rieder et al., 2010; Weihs et al., 2008, 2013), to the role of aerosols in alpine valleys (e.g. Blumthaler et al., 1997; Wuttke et al., 2012) and studies dealing



with anthropogenic influences on radiative fluxes and solar energy (e.g. Weihs et al., 2015) predominated in Austria.

On this background the Austrian RADiation monitoring network (ARAD) was founded in the year 2010, following an initiative of ZAMG in cooperation with the Universities of Graz and Innsbruck, and the University of Natural Resources and Life Sciences (BOKU) in Vienna. From its original concept, ARAD has to fulfil three major requirements: (i) providing a state-of-the-art national climate monitoring network, (ii) providing data for atmospheric model/satellite data calibration and validation; and (iii) providing high-precision data for further technical development in the field of solar energy utilization.

This paper presents the ARAD network with its aims, scopes and innovative approaches. First, Sect. 2 details the concept of ARAD, the stations network and the measurement setup. Section 3 illustrates the data processing and quality control. An uncertainty analysis presented in Sect. 4 explores the range for the combined expanded ¹⁵ uncertainty of all ARAD stations. In Sect. 5 the data policy, allocation and some examples of data usage are presented. Finally, Sect. 6 discusses some key points before the summary concludes the paper in Sect. 7.

2 Concept of ARAD

2.1 Aims of ARAD

- The general aim of ARAD is to establish a high precision long-term monitoring network for solar and terrestrial surface radiation in Austria in order to assess the status as well as the temporal and spatial changes of radiative fluxes at/to the surface. To this aim three general principles served as the basis for establishing the ARAD network: (i) to explore the potential of existing radiation measurements, or measurements with linkage
- to radiation (e.g. aerosols), (ii) to continue long-term observational series of radiation with known high quality and (iii) to capture the spatial patterns of the radiation climate in



Austria. Consequently, observations at 5 sites are routinely performed following, as far as practicable, the guidelines for surface radiation measurements established by the BSRN (McArthur, 2005). BSRN guidelines detail the standardization of observation methods (instrument specifications, site location, measurement and calibration proce-

dures, maintenance procedures and intervals) and data acquisition, storage and quality control. Although ARAD stays close to BSRN guidelines operational logistics at some sites require slight deviations from these.

The accuracy targets for BSRN irradiance measurements are (McArthur, 2005): 0.5% for direct normal, 2% for global and diffuse and 2% for downwelling infrared radiation.

2.2 Station network

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The ARAD network comprises currently 5 monitoring sites: Wien Hohe Warte (WHW; 198 ma.s.l.), Graz/University (GRZ; 398 ma.s.l.), Innsbruck/University (IBK; 578 ma.s.l.), Kanzelhöhe (KSO; 1540 ma.s.l., since 2013) and Sonnblick (SON; 3109 ma.s.l.) which are operating since 2011.

As can be seen in Fig. 1, ARAD currently covers 4 out of 5 so-called Coarse-Resolution Subregions (CRSs) defined in the HISTALP project (HIstorical Instrumental climatological Surface Time series, Auer et al., 2007). CRSs define sub-regions with common long-term trends for multiple climate parameters (air pressure, air tempera-

- ture, precipitation, sunshine duration and cloudiness) within the GAR. There are four CRSs in the horizontal domain (regions: Northwest, Northeast, Southeast, Southwest) and one in the vertical domain (high-elevation summit sites) defined. Currently besides the region Southwest, all CRSs are represented by at least one ARAD site. For comparison reasons, Fig. 1 shows the location of the automated stations of the national meteorological observing network of Austria (semi-automatic weather stations, section).
 - (TAWES), operated by ZAMG) measuring global radiation, too.

An additional ARAD site Klagenfurt (which will be operational by 2016) will provide along with the ARAD sites KSO and SON a unique vertical transect of radiation mea-



surements south of the Alpine main ridge within a relatively small horizontal distance (approximately 100 km) with very similar mesoscale synoptic conditions. This transect will allow to investigate vertical gradients of radiative fluxes with and without cloud effects, as well as effects of boundary layer dynamics and thickness, related to synoptic conditions and anthropogenic emissions, and turbidity effects on radiative fluxes.

It is important to mention that one of the ARAD sites, SON, is also included in the BSRN network (since January 2013; http://bsrn.awi.de/stations/listings.html). Due to some technical modifications (Sect. 2.4.4) and the regular maintenance of the on-site staff, the station SON offers continuous, all-weather radiation measurements at an exposed high-alpine site (3109 m a.s.l.). SON is the only radiation monitoring station that provides continuous measurements at BSRN level at that altitude in Europe. Addition-ally, SON is the second highest BSRN station worldwide following Station Concordia at Dome C, Antarctica (3233 m a.s.l.).

2.3 Station setup

- ARAD sites are equipped with four broadband radiation sensors which are suitable to BSRN requirements, mounted on a suntracker (see Fig. 2), for measurements of global (GLO), direct (DIR) and diffuse (DIF) solar radiation and downwelling longwave radiation (DLW). The suntracker allows correct tracking of the solar path; guarantees the continuous alignment of the pyrheliometer to record DIR and ensures continuous shad-
- ing of the pyranometer for measurements of DIF and the pyrgeometer for measurements of DLW. All radiation sensors used within ARAD are state-of-the-art thermopile instruments with specifications well within the limits recommended and accepted by BSRN. Following the ISO 9060 classification, all pyranometers used within ARAD are secondary standard instruments and all pyrheliometers are first class instruments. Further details on instrument specifications can be found in Table 1.

Within ARAD all horizontally mounted sensors are placed in ventilation units to reduce solar loading and thermal offsets. In addition all sensors are heated and ventilated (see Fig. 2) in order to reduce interference by rain drops, dew, rime, ice and snow de-



position on the instrument dome and to reduce temperature gradients that are known to occur between the glass dome and the instrument body due to IR losses (Philipona, 2002). For ARAD pyranometers and pyrgeometers we use the heating and ventilation system PMOD-VHS developed by the Physikalisch-Meteorologisches Observatorium

- ⁵ Davos (PMOD) in Switzerland (described in detail in Philipona, 2002) and the ventilation unit SBL 480 developed by the German manufacturer Eigenbrodt (see Fig. 3), though deviations from this baseline setup occur depending on the station (see Table 2 for site specific information). At KSO all radiometers are equipped with ventilation units CV 2 developed by manufacturer Kipp & Zonen. For one of the pyranometers and the
- ¹⁰ pyrgeometer at ARAD station GRZ we use a slightly different, self-designed system that places the heating not at the interface between instrument body and glass dome but at the bottom of the instrument which provides the possibility to change the rate of heating. ARAD sensors are using a general heating power of 10 W with the exception of station SON, where the power is increased to 25 W due to frequent snow and frost ¹⁵ conditions.

A correctly working heating and ventilation system should prevent so called nighttime zero offsets that occur due to IR losses of the glass dome. Thus, the night-time signal of the pyranometers is a direct quality indicator for the thermal control system. We note that the heating effect on the dome due to the fan motors is nullified when wind speeds are moderate to high.

2.4 Measurement variables, sampling rates, data acquisition, and instrument maintenance

2.4.1 Calibration of ARAD instruments

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ARAD pyranometers are calibrated through comparison with a working standard pyra nometer (International Organisation for Standardization, 1992) at ZAMG headquarters in Vienna or sent for calibration to the instrument manufacturer Kipp & Zonen. The calibration procedure at ZAMG is based on the direct comparison of one minute average



values (with a sampling rate of 1 Hz) during periods with GLO exceeding 600 Wm^{-2} between 09:00 and 13:00 UTC. The Kipp & Zonen indoor calibration procedure is based on a side-by-side comparison with a reference pyranometer fed by an artificial sun. To insure continuous measurements at all ARAD stations, instruments undergoing calibration are immediately substituted by calibrated sensors of the same manufacturing type.

The working standard of ZAMG itself is calibrated using the traditional so-called "sunand-shade" calibration method (International Organisation for Standardization, 1993). Thereby the working standard is calibrated against a cavity radiometer at ZAMG head-

- quarters in Vienna (TMI, serial number 68025) that participates in the international pyrheliometer comparison (IPC) exercise in Davos, Switzerland every 5 years. This procedure ensures that the reference TMI cavity radiometer is traceable to the World Radiometric Reference (WRR) in Davos, Switzerland (Fröhlich, 1991).
- It is important to note that this procedure differs from BSRN suggestions for pyra-¹⁵ nometer calibration, which recommend the "alternate method" of Forgan (1996). The "Forgan" method is based on swapping both pyranometers measuring GLO and DIF and calculating the calibration coefficients based on simultaneous equations of GLO given by the component sum of DIF and DIR before and after the swap for specific solar zenith angles. BSRN recommends this procedure as it allows for on-site instrument calibration and avoids thermal shocks of the instrument that may occur when using the
- ²⁰ calibration and avoids thermal shocks of the instrument that may occur when using the traditional sun-shade method (Forgan, 1996).

Despite this recommendation the ARAD consortium utilizes the "sun-and-shade" method for instrument calibration because: (i) this approach is also used for calibration of Schenk star pyranometers of TAWES of ZAMG and thus provides traceability of all

ZAMG radiation sensors to one common standard, (ii) it avoids the use of a travellingstandard pyrheliometer at all sites which would be necessary using the Forgan method, (iii) long comparison intervals under stable clear-sky conditions are used for calibrating the reference pyranometer to avoid thermal shocks.



For pyrgeometers, optimal standard methods of calibration and traceability to an absolute irradiance scale are still under debate (Gröbner et al., 2014, 2015; Philipona, 2015). Thus, BSRN recommends sending pyrgeometers to PMOD Davos for calibration with a black body cavity (McArthur, 2005). Every two years, ARAD pyrgeometers

- ⁵ are sent to Kipp & Zonen for calibration. The calibration procedure is traceable to the World Infrared Standard Group (WISG) in Davos consisting of four reference pyrgeometers, building a long-term stable reference (Gröbner et al., 2014). This calibration procedure avoids the necessity of a site reference instrument because each pyrgeometer is directly traceable to WISG.
- ¹⁰ Finally, all ARAD pyrheliometers are calibrated by direct comparison (International Organisation for Standardization, 1990) against the TMI cavity radiometer, the latter participating regularly at the IPC in Davos, and thus are directly traceable to the World Radiometric Reference (WRR).
- At BSRN/ARAD site SON, the calibration of all instruments is performed annually, as recommended by BSRN. At other ARAD sites instrument calibration is performed every two years. Long-term stability analysis of ARAD radiometer sensitivities (based on different calibration certificates of the same instrument at different times) indicates that the relative change of the calibration factor over two years is well below 1 % for all pyranometers and < 0.2 % for all pyrheliometers operated within the ARAD network.

20 2.4.2 Measurements

The radiation components GLO, DIR, DIF and DLW are the key variables measured at each ARAD site. Besides these radiation components data on body temperature of all sensors and the heating power and ventilation of pyranometers is recorded at all ARAD sites except KSO.

Data sampling takes place at 1 Hz (GRZ, IBK, SON, WHW) and 10 Hz frequency (KSO) with the following one minute statistics calculated and stored: average, standard deviation, minimum and maximum. An example plot of the measured irradiances at station SON during one day is shown in Fig. 4.



A specific data acquisition system (DAQ), developed by Logotronic (http://www. logotronic.at/), is used at all ARAD sites except KSO. The DAQ is calibrated over the entire voltage range with a resolution of 10 μ V. The accuracy of the voltage measurement from the data acquisition and logging system equals $\pm 10 \mu$ V, which corresponds

- to roughly 0.8 to 1.4 W m⁻² (given the range of calibration factors of radiometers within the ARAD network; see Table 1). The ARAD site KSO uses an upper tier data logger system from Campell Scientific (http://www.campbellsci.com) throughout its operations with an analog input accuracy of ± 0.07 % of reading plus an offset of 2.005 µV and a resolution of 0.33 µV.
- ¹⁰ A traceable reference voltage generator (RVG) is used to periodically (every two years) recalibrate the DAQ at all ARAD stations. Results from RVG measurements suggest that a potential zero offset is < $10 \,\mu$ V and thus smaller than the accuracy of the acquisition system. An additional quality assurance is provided by the nighttime pyrheliometer measurements, which should not suffer from possible thermal offsets. This
- ¹⁵ data shows no negative radiation signals and thus provides independent confidence in the voltage measurement of the DAQ. The temperature dependence of the DAQ relative to the reference temperature during calibration with the RVG equals 0.4 μ V °C⁻¹ at all stations except KSO. At the latter the temperature dependence is already corrected during logging.
- ²⁰ Complementary to ARAD radiation data, basic meteorological records of air temperature, air pressure, relative humidity, precipitation, sunshine duration, wind speed and direction and global radiation (measured with a black and white pyranometer, a Schenk star pyranometer) from the collocated TAWES station are also stored as 1 min averages or sums in the same database. For details on meteorological observation methods and ²⁵ related uncertainties the interested reader is referred to Haiden et al. (2011).

2.4.3 Instrument maintenance

ARAD instruments are regularly inspected and maintained by human observers. Maintenance intervals are at maximum one week within the ARAD network. At three sites,



the BSRN site SON, KSO and GRZ instruments are maintained on daily basis, as recommended by BSRN.

Maintenance tasks are defined corresponding to BSRN standards and regulated in a maintenance manual and follow a defined number of checks. These include: (i)

- ⁵ cleaning and levelling of all instruments, (ii) visual inspection of cables, ventilation and heating devices and (iii) the control of the sun tracking system and shading of the instruments recording HIM and DLW. Immediately after maintenance, the results of the check are entered in a web interface and stored in a central database for further processing and use. On an annual or biennial basis the heating and ventilation systems
- ¹⁰ are cleaned and a control and service of the sun tracking system is performed following recommendations by the manufacturer. Apart from these routine and regular maintenance tasks, occasional service is required whenever failed checks by the human observer or the automated or manual data quality analysis (see Sect. 3.2) make this necessary.

15 2.4.4 Special configurations at BSRN site SON

Due to the exposedness and harsh weather conditions of the site, the ARAD and BSRN station SON required the following technical adaptations: (1) for data quality assurance the heating and ventilation power of a pyranometer or pyrgeometer (see Sect. 2.3) is connected to one single electrical circuit per instrument. In case of a single failure of the

- ventilation (due to e.g. ice formation) the heater is also immediately turned off avoiding differential heating leading to additional thermal offsets. (2) Before operational use of the Hukseflux DR02 pyrheliometer with heated front window, different shading and heating experiments were performed to determine the ideal heating power between maximum frost removal efficiency and minimum thermal offsets, which was found to be
- 25 2.1 W. A comparison of DIR using the heated DR02 (corrected with temperature dependence) and an unheated CHP-1 pyrheliometer over 11 clear-sky days during a two year period showed a mean relative difference of -2.0% (±0.18% expanded uncertainty). This is well within the differences found between different pyrheliometers of the



same type when compared to open cavity radiometers in an extensive pyrheliometer intercomparison exercise (Michalsky et al., 2011). (3) At station SON we use heating and ventilation devices produced by the German manufacturer Eigenbrodt. The radiation shield of these is a bit lower leading to less cut offs during sunrise and sunset.

- Further the systems offers a fixing system of the radiation shield and an easier to handle external levelling system where the screws are bigger and mounted from below (see Fig. 3). (4) To reduce problems with frost and ice we mounted 0.2 m long and 0.05 m wide plastic tubes to the inlets of the heating and ventilation system beneath the pyranometers and pyrgeometers at station SON replacing the grid that usually prevents the
- ¹⁰ instruments from insects, large aerosols and pollen, as these do not pose a problem at high elevations. This modification has proven to effectively delay the buildup of rime that could otherwise easily become thick enough to disturb and reduce the ventilation and thus the heating effect on the glass dome, leading to rime formation on the domes and attenuation of any irradiance signal (see Fig. 3).

15 **3 Data**

3.1 Operational data processing

After being measured and recorded, all parameters (see Sect. 2.4.2), are immediately stored in a Sybase database at ZAMG in Vienna. The ARAD convention is thereby to store both the raw voltage signal of the radiative fluxes and the irradiance in Wm^{-2}

- ²⁰ converted from the raw signal using the individual calibration factor of the instrument. We note that currently no automated correction of the calibration factor for temperature effects is applied for most ARAD sensors (those provided by Kipp & Zonen) as such correction is considered negligible (well within ± 0.5 % between -20 and +50 °C relative to +20 °C).
- ²⁵ One exception in this respect is the front-window heated Hukseflux DR02 pyrheliometer operated at SON. For this instrument temperature effects are not negligible



(estimated as 5 % at -30 °C), and an individual correction polynomial provided by the manufacturer is applied before data transmission to the ARAD data base (or the BSRN archive or other costumers).

3.2 Quality control

⁵ To maximize ARAD data quality we use a combination of a manual and two automated data quality control (QC) methods on daily and hourly resolution (weekend data are controlled at the beginning of the next week). The algorithms used for automated control are an extended version of those provided by Long and Shi (2008), see details below.

10 3.2.1 Manual quality control

The daily manual data QC consists of visual inspections of (i) the graph of the daily automated QC (see Sect. 3.2.2) from the previous day, (ii) a near-realtime, interactive data plot of all stations (updated every 5 min) of the one-minute average radiation values and DIR calculated on the horizontal surface to enable the comparison between GLO and its component sum DIR + DIF, (iii) review of automated e-mail alerts sent by

the hourly QC (see Sect. 3.2.3).

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3.2.2 Automated quality control

The daily automated QC consists of a script containing the QC criteria for all recorded radiation fluxes as described in Long and Shi (2008) as well as some additional criteria detailed below. The automated script is run daily for the data recorded over the last 24 h at all ARAD stations. For each station, the script reads a metadata file containing all relevant coefficients for criteria that have been established based on site specific data (e.g. upper climatological limits of fluxes as in Long and Shi (2008)).

In an initial step the automated QC creates quality flags for each recorded element and the records are modified from their initial value 0 (unchecked data) to either one



of the following four states: 1 (data checked and passed all tests successfully), 2 (data checked but wrong as at least one test failed), 3 (data checked but of questionable quality), 255 (missing data) and stored in separate tables of the data base.

In a second step a graphical summary of the daily automated QC is produced. This graph shows the time-series of the one-minute averaged radiation fluxes along with the cloud observations from the hourly SYNOP report from the closest available station and information about failed QC criteria from the automated QC as detailed below.

A third step in the QC procedure comprises the checking of 61 quality criteria. These criteria can be grouped into 4 types: (1) integrity tests (e.g. missing values), (2) outlier detections (2) min/may tests (e.g. avagadeness of pessible limits) and (4) comparison

detections, (3) min/max tests (e.g. exceedance of possible limits) and (4) comparison tests (e.g. GLO vs. component sum (DIR horizontal + DIF)). For further details on these quality tests the reader is referred to the work of Long and Shi (2008). During this QC process two tables are created per site in the data base containing the station specific coefficients needed for the automated QC and the daily summaries for errors that occurred during the check of 61 guality criteria.

Finally measured irradiance values are converted to units of Wm^{-2} using instrument specific calibration factors stored in a separate data base table. Besides that, irradiance solar position (azimuth and zenith) and the clear sky index (Marty and Philipona, 2000) are stored in this data base table. The clear-sky index is used to separate clear-sky from cloudy days in further analysis.

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Table 3 summarizes the 3 year average quality flag statistics for all stations operating since 2012. The fraction of data flagged as "good" equals depending on the measured parameter 74–85% at SON and 91–99% at the other stations. Note, that reduced values at station GRZ compared to WHW and IBK do not reflect a lower quality but ²⁵ more frequent daily maintenance (data is flagged as wrong during maintenance). The fraction of observations where data of all 4 parameters are simultaneously flagged as "good" ranges from 67% at SON to 88–94% at other ARAD stations. Lower data quality at BSRN station SON reflects the difficult measurement conditions at this exposed high-alpine site.



3.2.3 Hourly automated quality control

The hourly automated QC consists essentially of a strongly reduced set of criteria (most critical ones) from the daily automated QC and there is no writing of quality flags to any database, instead an email containing the error information is sent to the on-

site staff in case of failure of any of the criteria. Hourly checked criteria consist of all tests described in Appendix A plus a check for missing data. The outlier detection (Test (4) in Appendix A) is thereby not applied to the irradiance signals as during the daily automated QC but to the instrument case minus air temperature differences to detect eventual thermal offsets.

10 4 Uncertainty analysis of ARAD observations

In the following paragraphs we detail uncertainty estimates for all shortwave radiative fluxes measured at all five ARAD sites over the full annual cycle from 1 July 2014 to 30 June 2015.

4.1 Shortwave fluxes

¹⁵ The measurement equation for the shortwave fluxes (GLO, DIF and DIR) reads:

$$I_c = \frac{U}{S_c},\tag{1}$$

where I_c is the irradiance in Wm⁻², U is the raw signal (voltage) and S_c is the sensitivity given in μ V (Wm⁻²)⁻¹. The combined standard uncertainty U_i of the measured irradiance I_c is then, following Vuilleumier et al. (2014):

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$$U_j = \sqrt{\frac{u_s^2 U^2}{S_c^4} + \frac{u_u^2}{S_c^2} + u_{stat}^2 + u_{os}^2 \sum u_{op}^2}$$



(2)

where u_s and u_u are the standard uncertainties (Reda, 2011) of the sensitivity and the raw signal, respectively. The term u_{stat} is calculated following Vuilleumier et al. (2014) from the standard deviation of the 1 Hz irradiance data (with quality flag 1) measured during 1 min intervals at times when DIR is slowly varying. u_{os} is a correction factor compensating a potential offset due to a thermal effect (note: this applies only to pyranometer measurements). Finally, u_{op} are operational uncertainties that can affect either S_c or U and depend on the measured irradiance quantity such as e.g. leveling, soiling or directional response. As these uncertainties are expressed separately for a small (50 W m⁻²) and a large (1000 W m⁻² (GLO, DIR) and 500 W m⁻² (DIF)) signal, following the methodology by Vuilleumier et al. (2014).

The first term $\frac{u_s^2 U^2}{S_c^4}$ in Eq. (5) describes the uncertainty of the sensitivity. To derive the standard uncertainty of the sensitivity u_s the square root of the quadratic sum of the calibration uncertainty, provided for each instrument by the manufacturer, and

- ¹⁵ other uncertainties provided by the manufacturer (e.g., non-linearity, temperature dependence and aging) need to be taken into account. As those values are provided as expanded uncertainties, they need to be converted into standard uncertainties, i.e. by dividing through the coverage factor (1.96 in case of the calibration uncertainty, assuming a Gaussian distribution and $\sqrt{3}$ in case of the other 3 terms assuming a rectangular distribution, Reda (2011)). Results for shortwave instruments at ARAD sites are shown
 - in Tables 4 to 6.

The measurement uncertainty of the raw signal U is defined by the second term $\frac{u_u}{c^2}$

in Eq. (2). As described in Sect. 2.4.2, the accuracy of the voltage measurement is $\pm 10 \,\mu\text{V}$ at all ARAD stations except KSO and is non-proportional to the voltage signal.

²⁵ At the KSO site it is proportional and equals only 0.07 % of the reading plus 2.005 μ V. Following Vuilleumier et al. (2014) its distribution is assumed to be rectangular, so both accuracies have to be divided by $\sqrt{3}$ to obtain the standard uncertainties, $u_u = 5.8 \mu$ V at sites WHW, SON, IBK and GRZ and $u_u = \pm 0.04 \% + 1.15 \mu$ V at the KSO site. This



uncertainty values together with the sensitivities of the respective instruments are then used to calculate the second term of Eq. (2). The results for all five ARAD sites are shown in Tables 4 to 6.

The third term in Eq. (2) u_{stat} is derived from the standard deviation of the 1 Hz signal of the individual irradiance quantities at times when DIR is varying slowly. The results are also given in Tables 4 to 6 for all ARAD sites.

The estimation of the thermal offset uncertainty u_{os} (fourth term in Eq. 2) is more complicated. Its more or less intrusive direct measurement especially during daytime (Bush et al., 2000; Dutton et al., 2001; Ji and Tsay, 2010; Michalsky, 2005; Philipona, 2002) as well as its correction using other measured variables (Dutton et al., 2001; Haeffelin et al., 2001; Sanchez et al., 2015) was investigated in previous studies. A re-

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- Haeffelin et al., 2001; Sanchez et al., 2015) was investigated in previous studies. A recent study by Sanchez et al. (2015) concludes based on capping experiments, that observed daytime thermal offsets for both global and diffuse measurements are highest correlated with the diffuse fraction of the incoming solar irradiance. These authors
 ¹⁵ highlight also correlation with the ambient air temperature as well as the NetIR signal
- from a collocated pyrgeometer, in agreement with earlier work by Dutton et al. (2001).

To date no routine measurement of the pyrgeometer dome temperatures nor capping experiments are available for ARAD sites. Thus the detection of (daytime) thermal offsets is limited to the analysis of nighttime pyranometer data, as deviations from zero

- are assumed to be triggered by thermal offsets (Michalsky, 2005; Philipona, 2002). Unfortunately, the limited resolution and accuracy of the DAQ at most ARAD sites except KSO (see Sect. 2.4.2), corresponding to approximately 1 W m⁻² depending on the sensitivity of the instrument, does not allow a reasonable correlation analysis between the nighttime offsets and other variables such as the longwave net flux as the offsets are
 in the order of a few W m⁻². Therefore, the calculated median nighttime values of the
- GLO and DIF measurements are taken to estimate this uncertainty term (expanded uncertainty values). Results of all ARAD sites are detailed in Table 4 to Table 6.

The last term in Eq. (2) u_{op} expresses a sum of uncertainties that depend on the operational conditions and the maintenance level. These include soiling effects, levelling-



induced errors (only for GLO as we assume the influence on DIF being negligible) and a directional error also called cosine response uncertainty (only for GLO). The latter is not proportional to the voltage signal (and only relevant at times with $DIR > 0 W m^{-2}$) and provided by the instrument manufacturer. For CMP21 and CM22 sensors used in $_{5}$ ARAD these numbers are < 10 W m⁻² and < 5 W m⁻², respectively. Influence of soiling effects (excluding e.g. soiling by birds) is generally anticipated to be larger for pyrheliometers than for pyranometers (due to collimation) (Geuder and Quaschning, 2006; Michalsky et al., 1988; Myers et al., 2001). Following the results of Vuilleumier et al. (2014) the effect of soiling should be well below the 1 % level for regularly maintained instruments (i.e., cleaning performed at least several times a week). Follow-10 ing this for the ARAD sensors, potential soiling errors are neglected for pyranometer measurements (GLO, DIF) and a tentative value of 0.2% (SON, isolated high altitude site), 0.3% (KSO, alpine site at mid elevation), 0.4% (GRZ, urban site with daily maintenance), 0.8% (WHW, urban site with weekly maintenance) and 1.0% (IBK, urban site with less maintenance than WHW) soiling error is assumed for the pyrheliometer 15

- measurements (DIR). Finally, levelling-induced errors are only relevant for GLO measurements as these are induced by a tilt of the instrument during operation leading to an imprecise projection on an exact horizontal surface. Therefore, this error is a function of the azimuth and inclination of the tilted sensor, solar position and ratio of direct
- to global radiation. As ARAD radiometers are mounted on moving suntracking systems additional (diurnal) variations of this tilt would need to be considered which are neglected here. Following coarse estimates from case studies performed at several ARAD sites, this suntracker-induced levelling error may be in the order of a few tenths of degrees. Once an error on the levelling of the pyranometer is identified, it can be
- trigonometrically corrected in post processing. Ideally this is achieved by e.g. a digital level that logs the exact tilt and is mounted on the moving platform. In operational practice at ARAD sites a bubble level mounted on the pyranometers and pyrgeometers is controlled during maintenance; if the bubble is more than half outside a reference circle, the respective sensor has to be re-leveled by the on-site staff.



The leveling-induced uncertainty is estimated as follows: from operational experience (daily maintenance) in the ARAD network we estimate an average maximum slope of the sensor tilt of 1°. Then 10 min averages of quality controlled, measured DIR projected on the horizontal (DIR_{hor}) and DIF values over a full annual cycle are used as input to a radiative transfer model (using a simple isotropic assumption for diffuse radiation) to calculate the equivalent GLO value for a 1° tilted surface (GLO_{tilt}) and all azimuth directions in steps of 1°. A statistical analysis of the daily sums of the difference (DIR_{hor} + DIF) – GLO_{tilt} for all azimuth directions of the sensor tilt is performed to deduce an annual average of the daily maximum (worst azimuth) relative leveling-

¹⁰ induced error in GLO on site basis.

Results of the relative contributions of the individual standard uncertainties u_i and the combined expanded uncertainties U_i for all five ARAD stations are given in Table 4 to Table 6.

- Relative numbers of the combined expanded uncertainty for all ARAD sites in Ta-¹⁵ ble 7 can directly be compared with the BSRN target accuracies (see Sect. 2.1). Values for the combined expanded uncertainties of the ARAD sites range between 1.46 and 23.25 % (DIR at GRZ for a large signal and GLO at GRZ for a small signal, respectively). Thereby it is important to note that largest uncertainties (> 4.28 %) at all ARAD sites are found for a small signal of GLO (11.84–23.25 %). As suggested by the rela-
- tive uncertainty contributions in Table 4 to Table 6 this is mainly due to the directional error of the pyranometers. If this error and two minor ones (temperature dependency of DAQ and instruments) are corrected using the calibration certificate of the individual sensors, the combined expanded uncertainties reduce to a range of 1.4–5.2 %. After this correction, 70 % of valid measurements at the ARAD stations for a large signal
- of GLO or DIF are within or very close to the expanded BSRN target uncertainty of 2%. For small signals of GLO and DIF and small and large signals of DIR, targets are not met. Enhanced uncertainty analysis suggest that for GLO and DIF further uncertainty reductions are possible with a better DAQ (such as used at ARAD site KSO), an annual instead of biennial recalibration of the instruments and the corrections of



thermal offsets. For DIR, the sensitivity of the instrument is the main uncertainty and BSRN targets of 0.5 % seem not to be achievable with the current commercial available instrumentation as also indicated by Vuilleumier et al. (2014).

5 Data policy, allocation and examples of use

5 5.1 Data policy

ARAD data are available upon request from ZAMG for "bona fide research purposes", without commercial application or intentions in mind. A formal agreement has to be signed by the user to confirm the intentions of use and additional obligations related to the publication and use of the data. Quality controlled data from ARAD and
¹⁰ BSRN station SON are transferred on a monthly basis to the BSRN archive and are available there. A rss feed for the latest data from SON is available here: http://www.pangaea.de/tools/latest-datasets.rss?q=Project:BSRN+SON. General contact information about the ARAD project as well as an ARAD folder in German and English in PDF format for the general public is available on the ZAMG website (https://www.
15 zamg.ac.at/cms/de/forschung/klima/datensaetze/arad). Figure 5 shows an ARAD data snippet, displaying seasonal mean daily courses for GLO, DIR, DIF and DLW at all five ARAD sites for a full annual cycle.

5.2 Examples of use of ARAD data

5.2.1 Improving sunshine duration observations

Within a research project at ZAMG a method provided by Forgan and Dyson (2004) to use one minute radiation data statistics based on 1 Hz sampling as recorded in ARAD (average, minimum, maximum, standard deviation) to improve the calculation of sunshine duration from pyrheliometer measurements was tested and compared to 1 Hz records of a NIP pyrheliometer and measurements from a conventional sunshine dura-



tion sensor (Haenni-Solar) such as used at the TAWES stations of ZAMG at the station WHW for a period of 4 months. The excellent agreement between the new method and the NIP data (average daily differences of 3.7 min (0.8%) of sunshine duration) suggests the ARAD stations as an outstanding regional reference for sunshine duration
 ⁵ measurements in Austria using this new method, thereby continuously improving and verifying the routine measurement.

5.2.2 Validation of ECMWF forecasts

Forecasting cloudiness and surface radiation remains a major challenge for numerical weather prediction models. BSRN and ARAD measurements are used at the European Centre for Medium-Range Weather Forecasts (ECMWF) to evaluate forecasts of downward fluxes of shortwave and longwave radiation. Figure 6 shows verification results for Vienna for the period 1 January–31 December 2012. Two features are worth noting. There is a strong drop in correlation during autumn, in both the shortwave and longwave range. This is a recurring issue due to difficulties in representing low stratus

- in the model. As documented in Haiden and Trentmann (2015) it affects large parts of Central Europe. The transient drop of the shortwave flux in May, in contrast, was due to a specific weather situation at the beginning of that particular month. A humid and relatively unstable air-mass with weak pressure gradients was present over Austria at the time. Because of the absence of significant synoptic-scale forcing, cloud formation
- ²⁰ was mainly governed by mesoscale processes which are less well represented in the model due to the limits of resolution (16 km in 2012). This created relatively large day-time forecast errors over several days, affecting the monthly average of the shortwave skill. In addition to the monitoring of the operational forecast, surface radiation measurements are also used at ECMWF in the evaluation of new model versions, and for assessing the quality of satellite-derived radiation products.



5.2.3 Analysis and forecasts of radiation and snow

The cloud parameterization scheme for diffuse solar radiation of the solar radiation model STRAHLGRID developed at ZAMG (Olefs and Schoener, 2012) to provide gridded datasets of near-surface solar direct and diffuse radiation in near-realtime based

on the INCA nowcasting system, was developed using ARAD DIF measurements. The so-called HIMratio factor is thereby defined by the ratio of measured to clear-sky modelled diffuse radiation correlated with MSG-2 satellite cloud types. More details and related figures can be found in Sect. 2.3 of the paper by Olefs et al. (2013) that also describes the coupling to the operational energy-balance snow-cover model SNOW GRID, showing the added-value of ARAD data for applications in alpine hydrology and cryosphere.

Recently, a method was successfully tested at ZAMG to improve area-wide 72-H DIR forecasts driven by atmospheric data of the ALARO NWP model used at ZAMG through a coupling of the high resolution STRAHLGRID model. For stations with sig-

nificant horizon shading, a reduction of the RMSE of 3–40 % could be achieved due to the better resolved topography. For stations in the lowlands an improved cloudiness scheme in STRAHLGRID based on ARAD data lead to a RMSE reduction of 25 % on average.

6 Discussion

Following the uncertainty analysis documented in this paper, there may be three future activities: (1) it will be possible to correct some of the identified uncertainty sources in the data during post-processing (e.g. cosine-response, thermal offset, levelling, temperature dependence, soiling) which will partly need additional measurements (no correction for historical data possible: e.g. levelling: a digital level for every sun-tracker)
 or experiments (historical data correction possible: capping for daytime thermal offsets, soiling: analyze data after vs. before maintenance) or simply using the calibration



certificates as was demonstrated (historical data correction possible: e.g. directional response) thereby reducing the combined uncertainties given in Table 7 closer towards BSRN targets. (2) It may become necessary to provide those uncertainty calculations operationally as meta information additionally to the allocated data using measured

- ⁵ irradiances in the full time resolution of one minute and technical specifications of the individual sensors. As some of the uncertainty components depend also on the actual short-term fluctuations of the meteorological conditions (e.g. directional or levelling error only relevant when DIR > 0) this would allow the user to better judge the actual uncertainty of the delivered data snippet especially in relation to the uncertainty in-
- ¹⁰ herent to e.g. a compared model or differently measured data. (3) Compare the here calculated sensitivity uncertainties u_s using this method with data analysis by comparison of redundantly measured parameters (e.g. GLO vs. DIF when DIR = 0, or GLO vs. the component sum DIR_{hor}+ DIF) as done in Vuilleumier et al. (2014) in order to check the plausibility of some of the derived values.
- ¹⁵ For some of the uncertainty components such as thermal offsets for pyranometer measurements, attempts were undertaken to improve the error correction with the current available data. In correlation experiments of the nighttime offsets with the longwave net flux, a rather low coefficient of determination of 0.31 was found and even multiple correlations including additionally e.g. the air temperature, wind speed, case temper-
- ²⁰ atures or the clear-sky index (Marty and Philipona, 2000), the latter related to cloud cover, could only increase r^2 towards 0.56. We attribute this rather poor performance to the stepwise signals of the nighttime offsets induced by our DAQ resolution as correlations found in most other studies are significantly higher. Our current approach using the median of the observed nighttime values of the GLO and DIF pyranometer
- signals at the individual stations has two drawbacks: (1) it is a time-constant, biaslike uncertainty estimation and not an uncertainty expressed as a function of changing meteorological conditions that in reality trigger the thermal offsets, (2) it only captures nighttime thermal offsets; and as daytime offsets have the same sign but are roughly



2–3 times larger than nighttime offsets (Sanchez et al., 2015) and references therein), this certainly underestimates the average uncertainty.

A comparable uncertainty estimate for DLW was beyond the scope of this study and is left for future work. However, comparing the average expanded sensitivity uncertainty

- of our CGR4 pyrgeometers of 4.1 % (see Table 1) with the BSRN target of 2 % suggests that targets are not met as operational and other uncertainties even add to this value of sensitivity uncertainty. In this relation we did also not investigate a possible sensitivity of the calibration coefficients of our CGR4 pyrgeometers with respect to integrated water vapour (IWV) related to dome spectral transmissivity as suggested by Gröbner
 et al. (2014) especially for climates with low IWV values. On the other hand this issue might be of minor importance for ARAD as all ARAD CGR4 pyrgeometers were built after the year 2003. Preliminary results suggest that those instruments suffer much
 - less from the IWV dependency issue (Gröbner and Wacker, 2013).

7 Summary and conclusions

¹⁵ We presented the Austrian Radiation monitoring network (ARAD), comprising currently 5 stations, which follows largely the quality standards and guidelines of BSRN. One ARAD site, Sonnblick (SON), is part of the BSRN network since January 2013.

Our main conclusion is that ARAD could serve as a powerful example for establishing state-of-the-art radiation monitoring at the national level with a multiple-purpose

- ²⁰ approach. In particular, we hope that our experiences will give a stimulus for radiation monitoring in other countries/regions worldwide, which is of utmost importance for climate change research. Instrumentation, guidelines and tools (such as the data quality control) developed within ARAD are best practices which could be adopted for other regions.
- ²⁵ The consistently defined measurement methods and automated and manual data quality control mechanisms present some innovative aspects to increase data availability and quality. Special care is taken at ARAD/BSRN station SON were rough weather



conditions necessitate a strict control, regular maintenance and adapted measurement methods. Average combined quality flags (automated and manual controls) of the last three years of operation indicate a high ratio of 74–85 and 91–98 % of data judged as "good" by those strict checks for stations SON and the other stations, respectively.

- ⁵ A detailed combined uncertainty analysis of the shortwave radiation fluxes at all five ARAD stations indicates that the combined expanded uncertainties range from 1.46 to 4.28 % with the exception of global radiation (GLO) for a small signal (50 W m⁻²), where combined expanded uncertainties equal 11.84 to 23.25 %. The large expanded uncertainties are due to a directional error of the pyranometers that is currently not
- ¹⁰ corrected for but can be corrected retrospectively using the calibration certificate of each instrument. Doing this would reduce combined uncertainties of 70 % of the ARAD stations below or very close to 2 % in case of a large signal of GLO or DIF (1000 and 500 W m⁻², respectively) corresponding to the BSRN target accuracy. For small signals of GLO and DIF targets could be met using an even better data acquisition
- system, a more frequent recalibration of the instruments and a correction of thermal offset errors. Similar to other studies, we conclude that the BSRN target accuracies of DIR can only be achieved with improved instruments. Corrections of the historical data and additional measurements in the future will help to further reduce those uncertainties. Furthermore, the operational calculation of these uncertainties and the inclusion as meta information together with the measured and guality controlled data is planned
- as a service for the community.

Besides meeting the requirements of a national climate monitoring network, ARAD data can thus serve the international climate research and impact community as well as for practical application questions related to solar energy or energy balance. Thus,

²⁵ ARAD provides comprehensive, high-quality and consistent irradiance reference data for comparison with satellite measurements, model applications (regional climate models, numerical weather prediction models, energy balance models) and other measurements (e.g. sunshine duration or radiation).



Appendix A: Additional quality criteria

Here we summarize the quality criteria used in the automated QC (see Sect. 3.2.2) of the ARAD data and that are not described in the study of Long and Shi (2008):

1. Based on experience, for every one-minute time step t_i we compare the measured sunshine duration SSD of the collocated TAWES station using a Haenni Solar 111B sunshine detector (sum of seconds with sunshine within one minute) with the one-minute average value of the ARAD DIR measurement. An error occurs if one of the two following conditions are met:

 $DIR(t_i) > 100 W m^{-2} \& SSD(t_i) = 0$

- $DIR(t_i) = 0 W m^{-2} \& SSD(t_i) = 60$
- 2. For every one-minute time step t_i we compare the current Hv of the heating and ventilation systems of all pyranometers and pyrgeometers to a defined threshold Hv_{lim} that depends on the measured parameter and the ARAD station and ranges between 0.1 and 0.3 A. An error occurs if the following condition is met:

 $Hv(t_i) < Hv_{lim}$

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- 3. For every one-minute time step t_i we compare one-minute average values of GLO_{ARAD} and DIF_{ARAD} (the latter only at ARAD stations WHW and GRZ) measured by the collocated TAWES (GLO_{TAWES}, DIF_{TAWES}). An error occurs if one of the two following conditions are met:
- $|\text{GLO}_{\text{ARAD}}(t_i) \text{GLO}_{\text{TAWES}}(t_i)| > 50 \text{ W m}^{-2}$ $|\text{DIF}_{\text{ARAD}}(t_i) - \text{DIF}_{\text{TAWES}}(t_i)| > 70 \text{ W m}^{-2}$
 - 4. For every one-minute time step t_i we compare the difference of the actual one-minute average value of all irradiances and the respective daily averages 10690



(A1)

(A2)

(A3)

 $(GLO_{mean}, ...)$ to a multiple (mult) of the standard deviations $(GLO_{std}, ...)$ of those quantities in order to detect outliers. The dimensionless factor mult is thereby calculated based on data analysis, for each station and parameter with ranges between 1.5 and 4. An error occurs if the following condition is met (example shown only for GLO):

 $(GLO(t_i) - GLO_{mean}) > mult \cdot GLO_{std}.$

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Table 1. List of measurement instruments used at ARAD stations.

Parameter	Manufacturer	Тур	ISO-9060 classification	Spectral range [nm]	sensitivities min/max/(mean) [µV W ⁻¹ m ⁻²]	expanded uncertainty range min/max/(mean) [%]	
DIR	Kipp & Zonen	CHP1	first class	200-4000	7.62/8.02/7.78	1.1/1.1/1.1	
DIR	Hukseflux	DR02-T	first class	200-4000	10.05/11.93/10.97	1.3/1.5/1.4	
GLO	Kipp & Zonen	CMP21	secondary standard	285–2800	8.29/12.75/9.52	1.4/1.5/1.5	
GLO	Kipp & Zonen	CM22	secondary standard	200-3600	9.15/9.19/9.17	1.0/1.0/1.0	
DIF	Kipp & Zonen	CMP21	secondary standard	285–2800	8.29/12.75/9.52	1.4/1.5/1.5	
DIF	Kipp & Zonen	CM22	secondary standard	200-3600	9.15/9.19/9.17	1.0/1.0/1.0	
DLW	Kipp & Zonen	CGR4/CG4	<u> </u>	4500–42 000	6.70/15.25/10.78	1.9/5.6/4.1	

Wien	Graz	Innsbruck	Sonnblick	Kanzelhöhe
48.25	47.08	47.26	47.05	46.68
16.36	15.45	11.38	12.96	13.90
198	398	578	3109	1540
10.4	9.8	9.4	-5.1	4.6
651	885	911	2263	1103
Flat/Urban	Flat/Urban	Mountain	Mountain	Mountain
		valley/Urban	top/Rural	top/Rural
Solys 2		Solys 2		Solys 2
	2 AP		2 AP	
2xCMP21,	2xCMP21,	2xCMP21,	2xCMP21,	2xCM22,
1xCHP1,	1xCHP1,	1xCHP1,	1xDR02,	1XCHP1,
1xCGR4	1xCGR4	1xCGR4	1xCGR4	1xCG4
PMOD-VHS	Eigenbrodt/	PMOD-VHS	Eigenbrodt	Kipp & Zonen
	self-designed			
ZAMG	ZAMG/Uni Graz	ZAMG/	ZAMG	KSO/ZAMG
		Uni Innsbruck		
9 Feb 2011	31 Aug 2011	5 Jul 2011	1 Jan 2011	1 Jan 2013
	Wien 48.25 16.36 198 10.4 651 Flat/Urban Solys 2 2xCMP21, 1xCHP1, 1xCGR4 PMOD-VHS ZAMG 9 Feb 2011	Wien Graz 48.25 47.08 16.36 15.45 198 398 10.4 9.8 651 885 Flat/Urban Flat/Urban Solys 2 2 AP 2xCMP21, 2xCMP21, 1xCHP1, 1xCHP1, 1xCGR4 Eigenbrodt/ PMOD-VHS Eigenbrodt/ ZAMG ZAMG/Uni Graz 9 Feb 2011 31 Aug 2011	Wien Graz Innsbruck 48.25 47.08 47.26 16.36 15.45 11.38 198 398 578 10.4 9.8 9.4 651 885 911 Flat/Urban Flat/Urban Mountain valley/Urban Solys 2 2 AP 2xCMP21, 2xCMP21, 2xCMP21, 1xCHP1, 1xCHP1, 1xCHP1, 1xCGR4 1xCGR4 1xCGR4 PMOD-VHS Eigenbrodt/ PMOD-VHS self-designed ZAMG/ Uni Innsbruck 9 Feb 2011 31 Aug 2011 5 Jul 2011	Wien Graz Innsbruck Sonnblick 48.25 47.08 47.26 47.05 16.36 15.45 11.38 12.96 198 398 578 3109 10.4 9.8 9.4 -5.1 651 885 911 2263 Flat/Urban Flat/Urban Mountain valley/Urban Mountain top/Rural Solys 2 2 AP 2 AP 2 AP 2xCMP21, 2xCMP21, 2xCMP21, 2xCMP21, 1xCGR4 1xCGR4 1xCGR4 1xCGR4 1xCGR4 1xCGR4 PMOD-VHS Eigenbrodt/ self-designed ZAMG/ Uni Innsbruck ZAMG 2AMG ZAMG/Uni Graz ZAMG/ Uni Innsbruck ZAMG

Table 2. List of Metadata of the ARAD stations. Mean annual air temperatures (temp) and precipitation sums (precip) are given for the climatological period 1981–2010.



Table 3. Summary of the quality flag statistics (average of 2012–2014) for the measured parameters GLO, DIF, DIR, DLW at 4 ARAD sites operating since 2012 using the combined daily automated and manual QC including e.g. maintenance times. The last row ("Perfect") indicates the percentage of timestamps when all 4 parameters are simultaneously flagged as "good".

Flag	Wien [%]	Graz [%]	Innsbruck [%]	Sonnblick [%]
	GLO, DIF, DIR, DLW			
Good (1)	99/98/98/96	93/96/96/95	92/93/94/91	81/74/85/81
Wrong (2)	1/1/0/0	6/3/2/2	1/1/0/0	16/24/13/14
Dubious (3)	0/0/1/3	0/1/1/3	0/0/0/3	1/1/1/3
Missing (255)	1/0/0/0	1/1/1/1	5/5/5/5	1/1/1/1
"Perfect"	94	88	89	67



e 4. ons	in the p	eriod 1	to unce July 20	14 to 3	es aπec 0 June 2	2015.	rtwave m	Standarda	ients at a	all five A	RAD œ	The Au radiation r netv	ustrian nonitorin vork
	WHW	GRZ	IBK	KSO	SON	WHW	GRZ	IBK	KSO	SON	\Box		
					Sensitivi	ty factor (u.)					SC	M Ole	fs et al
DIR	1.28%	1.28%	1.28%	1.49%	1.53 %	0.65 %	0.65%	0.65%	0.76 %	0.78%			lo ot al.
GLO	1.90 %	1.98%	1.98%	2.55%	1.53 %	0.97 %	1.01%	1.01%	1.30 %	0.78%	ŝ		
DIF	1.90%	1.90%	1.97%	2.55%	1.53 %	0.97%	0.97%	1.01%	1.30 %	0.78%	0		
				Uncertain	ty of the raw	signal U/of th	ne DAQ (u_{μ})						
DIR	10 µV	10 µV	10 µV	0.07 %	10 µV	5.77 μV	5.77 µV	5.77 μV	0.04 %	5.77 µV	P	Title	Page
				+ 2 μV					+1.15μV		dr		J
GLO	10 µV	10 µV	10 µV	0.07%	10 µV	5.77 μV	5.77 µV	5.77 µV	0.04 %	5.77 μV	Ð	Alberturent	In the design of the
				+2μV					+1.15μV			Abstract	Introductio
DIF	10 µV	10 µV	10 µV	0.07%	10 µV	5.77 μV	5.77 µV	5.77 µV	0.04 %	5.77 μV			
				+2μV	o				+1.15μV			Conclusions	Reference
					Statistical u	ncertainty (u _{sta}	at)	0.000/	0.05.0/	0.000/	_		
DIR						0.37%	0.29%	0.22%	0.25%	0.29%	\Box		
GLO						0.33%	0.29%	0.22%	0.3%	0.4%	SC	Tables	Figures
DIF				0	nerotional	0.23%	0.21%	0.15%	0.62 %	1.1%	Ě		
				U	perational u	meentainties ((_{op})				S		
~ ~	0	0.00-2	-2	2	1. The		1.0014/2	0.51.14/2	0.51.14/2	0.51.14/2	÷.		51
GLU	0 _2	2 w m	1 VV m	1 VV m	1 VV m	0	1.02 W m	0.51 W m	0.51 W m	0.51 W m	n		
DIF	1 W m -	0	1 W m -	1 W m -	1 W m -	0.51 Wm -	0	0.51 W m -	0.51 W m -	0.51 W m -			
	_2	_2	_2	_2	2. Direc	tional error	_2	_2	_2	_2	a	▲	▶
GLO	10 W m	10 W m	10 W m	5 W m	10 W m	5.77 Wm	5.77 W m	5.77 W m ⁻	2.89 W m ⁻²	5.77 W m	þe		
					3.	Soiling					-	Pool	Close
DIR	0.8%	0.4%	1.0%	0.3%	0.2 %	0.41%	0.2%	0.51%	0.15%	0.1 %		Баск	Close
~ ~	0.70.0/	0.00/	0.01.0/	1 00 0/	4. L	evelling	0.44.0/	0.40.0/	0.50.0/	0.40.0/			
GLO	0.76%	0.8%	0.91%	1.02%	0.9%	0.39%	0.41%	0.46%	0.52%	0.46%		Full Scre	on / Fec

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Table 5. Same as Table 4 but relative contributions of uncertainty components to total combined uncertainty. Uncertainties are given for a small (ss: 50 Wm^{-2}) and a large (ls: 500 Wm^{-2} for DIF and 1000 Wm⁻² for DIR and GLO) signal.

	Contribution (%) ^a										
			SS					ls			
	WHW	GRZ	IBK	KSO	SON	WHW	GRZ	IBK	KSO	SON	
Sensitivity factor (u_s)											
DIR	15	14	10	74 ^b	34	58 ^b	76 ^b	57 ^b	87 ^b	86 ^b	
GLO	1	1	1	5	0	61 ^b	63 ^b	63 ^b	79 ^b	46 ^b	
DIF	24	29	21	53 ^b	17	92 ^b	93 ^b	94 ^b	81 ^b	33	
		Unce	rtainty	of the ra	aw signa	al U/of th	e DAQ	(u _u)			
DIR	75 ^b	82 ^b	83 ^b	15	61 ^b	1	1	1	≈ 0	0	
GLO	1	1	2	0	1	≈ 0	≈ 0	≈ 0	≈ 0	0	
DIF	48 ^b	70 ^b	56 ^b	3	50 ^b	2	2	2	≈ 0	1	
			St	atistical	uncerta	ainty (u _{sta}	t)				
DIR	5	3	1	8	5	19	15	7	9	12	
GLO	≈ 0	≈ 0	≈ 0	≈ 0	0	7	5	3	4	12	
DIF	1	1	≈ 0	12	33	5	4	2	18	66 ^b	
			Ope	erationa	l uncert	ainties (u	(_{op})				
				1. Tł	nermal e	effect					
GLO	0	3	1	3	1	0	1	0	0	0	
DIF	27	0	22	33	0	1	0	1	0	0	
	h	h.	h	2. Dir	ectional	error					
GLO	98 ⁰	95 ⁰	96 ⁰	91 ⁰	97 ⁰	22	21	21	4	25	
	-			3	3. Soilin	g	_				
DIR	6	1	6	3	1	23	7	35	4	1	
	0	0	~	4.	Levelli	ng	10	10	10	10	
GLO	≈ 0	≈0	0	1	0	10	10	13	13	16	



^a Contributions that are assumed negligible (soiling for GLO and DIF, thermal effect for DIR and levelling for DIR and DIF) are not included in the table.

^b The largest contributions per measured quantity and station.

Table 6. Same as Tables 4 and 5 but products of sensitivity factor c_i and standard uncertainty u_i . Numbers are given for a small (ss: 50 W m⁻²) and a large (ls: 500 W m⁻² for DIF and 1000 W m⁻² for DIR and GLO) signal.

	$c_i^2 u_i^2 (W^2 m^{-4})$										
			SS			ĺ		ls			
	WHW	GRZ	IBK	KSO	SON	WHW	GRZ	IBK	KSO	SON	
Sensitivity factor (u_s)											
DIR	0.1	0.1	0.1	0.1	0.2	42.5	42.5	42.5	57.5	60.7	
GLO	0.2	0.3	0.3	0.4	0.2	94.0	101.6	101.6	169.0	60.7	
DIF	0.2	0.2	0.3	0.4	0.2	23.5	23.5	25.4	42.3	15.2	
Uncertainty of the raw signal U/of the DAQ (u_{ij})											
DIR	0.5	0.7	0.9	≈ 0	0.3	0.5	0.7	0.9	0.3	0.3	
GLO	0.4	0.5	0.6	≈ 0	0.5	0.4	0.5	0.6	0.3	0.5	
DIF	0.5	0.6	0.7	≈ 0	0.5	0.5	0.6	0.7	0.1	0.5	
			5	Statistic	al uncer	tainty (u	_{stat})				
DIR	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0	13.7	8.4	4.8	6.3	8.4	
GLO	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0	10.9	8.4	4.8	9.0	16.0	
DIF	≈ 0	≈ 0	≈ 0	0.1	0.30	1.3	1.1	0.6	9.6	30.3	
			O	peration	al unce	rtainties	(u _{op})				
				1.	Therma	l effect					
GLO	≈ 0	1.0	0.3	0.3	0.3	≈ 0	1.0	0.3	0.3	0.3	
DIF	0.3	≈ 0	0.3	0.3	0.3	0.3	≈ 0	0.3	0.3	≈ 0	
				2. C)irection	al error					
GLO	33.3	33.3	33.3	8.3	33.3	33.3	33.3	33.3	8.3	33.3	
					3. Soili	'ng					
DIR	0.0	0.0	0.1	≈ 0	≈ 0	16.7	4.2	26.0	2.3	1.0	
					4. Level	ling					
GLO	0.0	0.0	0.1	0.1	0.1	15.0	16.7	21.6	27.1	21.1	

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Table 7. Same as Tables 4–6, but combined uncertainties affecting shortwave measurements at all ARAD sites. Relative combined expanded values are marked in bold to allow the comparison with BSRN target accuracies (see Sect. 2.1).

	Expanded (Wm ⁻²)									
			SS					ls		
	WHW	GRZ	IBK	KSO	SON	WHW	GRZ	IBK	KSO	SON
DIR	1.7	1.7	2.0	0.9	1.3	16.8	14.6	16.9	16.0	16.4
GLO	11.4	11.6	11.5	5.9	11.5	24.3	24.9	25.0	28.7	22.5
DIF	1.9	1.8	2.1	1.8	1.9	9.9	9.8	10.2	14.2	13.3
					Expand	ded (%)				
			SS		-			ls		
	WHW	GRZ	IBK	KSO	SON	WHW	GRZ	IBK	KSO	SON
DIR	3.33	3.48	4.04	1.72	2.62	1.68	1.46	1.69	1.6	1.64
GLO	22.88	23.25	23.04	11.84	22.95	2.43	2.49	2.5	2.87	2.25
DIF	3.86	3.55	4.28	3.51	3.74	1.98	1.97	2.03	2.83	2.66
				:	Standard	(Wm^{-2}))			
			SS			, ,		ls		
	WHW	GRZ	IBK	KSO	SON	WHW	GRZ	IBK	KSO	SON
DIR	0.9	0.9	1.0	0.4	0.7	8.6	7.5	8.6	8.2	8.4
GLO	5.8	5.9	5.9	3.0	5.9	12.4	12.7	12.7	14.6	11.5
DIF	1.0	0.9	1.1	0.9	1.0	5.1	5.0	5.2	7.2	6.8
					$\sum c_i^2 u_i^2$	$(W^2 m^{-4})$				
			SS					ls		
	WHW	GRZ	IBK	KSO	SON	WHW	GRZ	IBK	KSO	SON
DIR	0.7	0.8	1.1	0.2	0.5	73.4	55.7	74.3	66.4	70.4
GLO	34.1	35.2	34.6	9.1	34.3	153.7	161.5	162.2	214.0	131.8
DIF	1.0	0.8	1.2	0.8	0.9	25.6	25.2	26.9	53.2	45.9





Figure 1. Topographic map (color-coded elevations) with ARAD stations (red points; Station Klagenfurt is planned to start operating in Autumn 2015), TAWES stations measuring GLO (grey points) and the coarse resolution subregions (CRS) defined as regions with common climatic variability (see text).





Figure 2. Typical ARAD Station: Suntracker with different radiation sensors. The picture in the lower right corner shows a pyranometer without radiation shield exposing the heating and ventilation system.





Figure 3. The modified Eigenbrodt heating and ventilation system with external sensor levelling as used for the ARAD stations (left) and some special modification to reduce snow and ice effects at ARAD/BSRN station SON: plastic tubes mounted at the inlet of the heating and ventilation system beneath the instruments (lower right) delay the built-up of rime leading to reduced ventilation and the accumulation of snow/ice on the pyranometer domes, deteriorating the radiation signal (upper right).





Figure 4. Sample of ARAD data measured at Station SON on 3 November 2014 between 06:00 and 15:00 UTC. GLO = global radiation on a horizontal plane, DIR = direct solar radiation on a plane normal to the direct beam, DIF = diffuse radiation on a horizontal plane, DLW = downwelling longwave radiation.





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Figure 5. Seasonal mean daily courses based on 10 min averages of the recorded and quality controlled 1 min average values for all measured irradiance quantities at all ARAD Stations for the full annual cycle 1 December 2013 to 30 November 2014.



Figure 6. Correlation between short-range (0–24 h) forecasts and observations of daily averaged values of downward shortwave and longwave flux at the ARAD station WHW. Shown are monthly means for the verification period 1 January–31 December 2012.

