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Extending the Calibration Traceability of Longwave Radiation Time-Series (ExTrac)

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Abstract. Pyrgeometers are used to measure longwave radiation at the Earth's surface that has been identified by the Global Climate Observing System (GCOS) as an Essential Climate Variable (ECV). The Baseline Surface Radiation Network (BSRN) has coordinated the measurement and archiving of radiation data at ground-based stations since the early 1990s. However, raw pyrgeometer data has not been archived by BSRN, and only exists in station archives themselves. In fact, data may no longer be available due to various legacy issues. This study reports a possible method to retrieve proxy values of raw pyrgeometer data from BSRN archives for periods predating the time when raw measurements were recorded along with processed data. Raw pyrgeometer datasets (1-min. resolution) and meteorological parameters from several BSRN stations were used to train a station-specific model. Using this data to re-calculate longwave radiation gives a root-mean-square-deviation of 1.7 – 4.6 and 1.9 – 4.8 Wm^{-2} (1-hr and 10-min data) with respect to original data that is less than the measurement uncertainty of ~4 – 5 Wm^{-2}.

INTRODUCTION

The Earth's surface radiation budget plays a crucial role in the climate system, hence accurately characterising components of the radiation budget is an important task. The Baseline Surface Radiation Network (BSRN; bsrn.awi.de; (1)) is one of several international networks to coordinate the measurement and archiving of radiation data. Downward and upward longwave radiation (DLR, ULR) measurements are conducted with pyrgeometers traceable to the World Infrared Standard Group (WISG) at the Physikalisch Meteorologisches Observatorium Davos / World Radiation Centre (PMOD/WRC; Davos, Switzerland). However, several important aspects concerning the traceability of the WISG as well as other instrumental issues remain to be resolved by the research community (2, 3). The first concerns the submission of DLR/ULR to the BSRN archive that may not be traceable to the WISG. The second concerns a re-scaling of the WISG (3, 4). The WISG is therefore currently regarded as an interim standard. If a re-scaling were to be approved by the WMO in the future, then longwave radiation time-series would need to be re-calculated. As a result, archived longwave time-series could be affected by positive changes of up to ~5 Wm^{-2} (3, 4), dependent on the prevailing sky conditions and water vapour content. These changes are significant in comparison to those expected from climate warming. However, a simple linear re-scaling of time-series is not possible due to the

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non-linear nature of the equation to calculate longwave radiation (see further below). This will require the original raw pyrgeometer data that may be difficult to obtain for a number of reasons: i) the possible loss of a knowledge-pool and/or the retirement of station scientists, and ii) the loss (or effective loss) of original datasets due to logistical or information technology issues. This study (Extending the Calibration Traceability of Longwave Radiation Time-Series; ExTrac) focuses on developing a methodology that could be applied to archived BSRN longwave radiation data to retrieve raw pyrgeometer data for periods predating the time when raw measurements were recorded along with processed data. The main aim of ExTrac is therefore to prevent the loss of legacy data and ensure their availability for future use when traceability and instrumental issues (2) have been resolved. Although BSRN has not routinely archived raw pyrgeometer data, this will soon be the case. At its last meeting in summer 2022, BSRN decided to make the recording and archiving of raw pyrgeometer data mandatory in the near future.

METHODS

Raw pyrgeometer data consists of the sensor voltage (U) and the instrument body (T_b) and dome (T_d) temperatures. Kipp & Zonen, Hukseflux and other pyrgeometers only measure T_b, while Eppleys measure both T_b and T_d. Pyrgeometers used at the BSRN stations in this study were all mounted on a solar tracker with a shading device to shield the dome from direct sunlight. In addition, all were operated with a ventilation unit, to help reduce riming at polar and high-altitude stations, and also to help in drying off rain droplets. To achieve this, incoming air is slightly warmed-up (typically <1°C) by a built-in heater. T_b and T_d are therefore not only representative of the ambient temperature (T_{2m}, at 2 m height) but also a small positive offset due to the heater. In order to explain the rationale of our approach, the Albrecht & Cox equation (5) to calculate DLR is shown below. Similar equations exist to calculate DLR (5), but the method detailed here can be applied to all.

$$DLR = \frac{U}{C}(1 + k_1\sigma T_b^3) + k_2\sigma T_b^4 - k_3\sigma(T_d^4 - T_b^4) \qquad 1)$$

DLR is given in units of Wm^{-2}, U is the thermopile sensor output (V), C is the pyrgeometer sensitivity ($VW^{-1}m^2$), σ is the Stefan-Boltzmann constant (5.6704×10^{-8} Wm^{-2} K^{-4}), T_b and T_d are in Kelvin, and k_i are the instrument constants. The k_3 term in Eq. 1 can be disregarded for pyrgeometers that only measure T_b. In the standard calibration procedure at PMOD/WRC, k_i are determined with a laboratory reference black-body, while C is determined relative to the WISG with outdoor night-time measurements during clear-sky conditions (6). When using DLR from the BSRN archive (DLR_{BSRN}), the retrieval of any one parameter out of U, T_b and T_d in Eq. 1 is trivial if the other two parameters are still available from station archives. However, if this is not the case then a retrieval is ill-posed. Despite this drawback, a promising semi-empirical method is the use of T_{2m} to replace T_b and T_d that is used here in a first attempt to retrieve raw data (referred to here as the basic model). The rationale of this approach is supported by the fact that: i) in-situ pyrgeometer and T_{2m} measurements are usually conducted within <10 - 20 m of each other, and ii) T_b and T_d are highly correlated with T_{2m}. As an alternative to T_{2m}, ambient temperature from ERA5 (5th generation ECMWF atmospheric reanalysis of the global climate) was also investigated. However, a time resolution better than 24 hours was not available for BSRN stations used here. Substituting T_b and T_d with T_{2m} in Eq. 1, and using DLR from BSRN then allows a proxy value of U to be retrieved (U_{proxy}). The root-mean-square deviation (RMSD) can be used as a representative statistic of the uncertainty of U_{proxy} with respect to U, and is useful to compare the results at different BSRN stations. However, such an RMSD (in units of volts) is not as intuitive as one in terms of DLR (Wm^{-2}). The RMSD of DLR_{proxy} vs DLR_{BSRN} is therefore determined here using U_{proxy}, T_b and T_d in Eq. 1. Note that using U_{proxy} and T_{2m} in Eq. 1 gives the original DLR.

After initial investigations, it was found that the basic model was unsuitable for several reasons (eg the last term in Eq. 1 cannot be used for Eppleys). Hence, the main modelling efforts focused on developing a more refined, station-specific model. Analyses determined that T_b - T_{2m} and T_d - T_{2m} had correlations of varying strength with several radiation and meteorological parameters. These included: i) global downward shortwave radiation (DSR) from BSRN, ii) wind speed (WS_{2m} at 2 m height) from BSRN and the BSRN stations, and iii) T_{2m} itself. A fourth parameter, the degree of cloudiness (cloud fraction) was occasionally used to further filter the above three parameters. Other parameters were also investigated (e.g. diffuse DSR, direct DSR, relative humidity, water vapour content, wind direction, etc) but only weak or no dependencies were found. After parameterisation, each of the above correlations (hereafter referred to as "module") was then used to generate proxy body and dome temperatures ($T_{b\,proxy}$, $T_{d\,proxy}$) with a 10-min or 1-hr resolution. The procedure for running the station-specific model consisted of several runs to identify the best combination of the three modules that gave the lowest RMSD value.

TABLE 1. BSRN stations (see https:\\bsrn.awi.de for further details) and the availability of time-series used in this study.

BSRN station	Location	Availability of BSRN meteorological and radiation data	Availability of raw pyrgeo. data in station archives	Raw pyrgeo. data used in this study
Cabauw (CAB)	Netherlands	2005 – present	2005 – present	2019 – 2021
Neumayer (GVN)	Antarctica	1982 – present	1982 – present	2006 – 2015
Ny Ålesund (NYA)	Svalbard	1992 – present	1992 – present	2006 – 2019
Payerne (PAY)	Switzerland	1992 – present	1992 – present	2007 – 2019
South Pole (SPO)	Antarctica	1992 – present	1992 – present	2008 – 2017
Syowa (SYO)	Antarctica	1994 – present	1994 – present	2011 – 2019

Meteorological and radiation time-series from BSRN stations listed in Table 1, were used in this study. In addition, all stations provided raw pyrgeometer time-series from their own station archives that are in principle, still available for the same time period as the BSRN time-series. However, it would have required a large effort by some stations to make time-series from the 1990s available. Hence, raw time-series from about 2006 onwards were used, as these were readily available. Considerable effort was spent in getting the raw pyrgeometer data into a common format for this study. Each station has its own format with a 1-min or even 1-sec resolution. Only CAB and GVN were able to provide raw pyrgeometer data in the so-called BSRN LR4000 data format (1-min resolution) that will become standard practice in the near future for all BSRN stations (7).

RESULTS, DISCUSSION AND CONCLUSIONS

Results from the analysis are shown in Figure 1 and Table 2. RMSD values for the basic model are in the ranges 4.1 – 26.1 Wm^{-2} and 4.6 – 26.1 Wm^{-2} for a 1-hr and 10-min data resolution, respectively. This compares to a current absolute uncertainty in DLR measurements of ±4.0 Wm^{-2} and to a range of 1 – 2 Wm^{-2} for calibration with respect to the WISG (3). For the station-specific model, the RMSD ranges decrease significantly to 1.7 – 4.6 Wm^{-2} and 1.9 – 4.8 Wm^{-2} (1-hr and 10-min). The main conclusions are summarised below.

TABLE 2. Root-mean-square deviation (RMSD) values are shown for a comparison of DLR_{proxy} with DLR_{BSRN} for basic and station-specific models. Pyrgeometer radiometer types: E = Eppley, K&Z = Kipp & Zonen.

BSRN Station	Pyrgeo. type	DLR_{proxy} vs DLR_{BSRN} RMSD (Wm^{-2})			
		Basic Model 1-hr data	Basic Model 10-min data	Station-Specific Model 1-hr data	Station-Specific Model 10-min data
Cabauw (CAB)	K&Z	9.0	9.0	2.3	2.4
Georg v. Neumayer (GVN)	E	4.4	4.6	2.4	2.8
Ny Ålesund (NYA)	E	4.1	4.6	2.2	3.1
Payerne (PAY)* (2007 – 2010)	E	9.8	9.9	3.5	4.5
(2011 – 2015)	K&Z	10.1	10.1	2.1	2.3**
(2016 – 2019)	K&Z	9.0	9.1	1.7	1.9**
(2013 – 2016)	E	9.9	10.1	2.4	2.7
(2016 – 2019)	E	7.9	8.0	2.1	2.5
South Pole (SPO)	E	26.1	26.1	4.6	4.8
Syowa (SYO)	K&Z	6.0	6.1	2.4	2.5

* Time-series from the main and backup BSRN pyrgeometers have been split-up to reflect periods when a change in pyrgeometer occurred or a change in the ventilation unit. ** Provisional RMSD values for a 1-min resolution give 2.4 and 2.0, respectively.

i) Our method demonstrates that 1-hr and 10-min proxy raw pyrgeometer data can be tentatively retrieved within the uncertainty of absolute DLR measurements at most stations in this study. Application of this method to other BSRN stations could then be conducted by training station-specific models with recent raw pyrgeometer data, allowing older parts of the raw time-series to be retrieved.

ii) A universal method that can be applied to any BSRN station without the training of a station-specific model was an initial aim, but our investigations suggest that this cannot be achieved within the desired accuracy. Although more complex, a station-specific model is the better approach. In addition, the retrieval of proxy raw data with a 1-min resolution was investigated as BSRN archived data has this resolution. A slightly higher uncertainty was found for selected datasets but the overall robustness of proxy data with this resolution would require further investigation.

iii) Our method may not be suited to all BSRN stations for several reasons: 1) On occasion, a poor correlation of T_b (and T_d) with T_{2m} was observed at some stations over time periods ranging from weeks to years. Analysis of web cameras installed on the measurement platforms of several Arctic and high-altitude stations suggest that this is mainly due to the riming of pyrgeometer ventilation units with snow and ice. The unstable long-term operation of ventilation units (i.e. air-flow and heating power issues) can also lead to a poor correlation. 2) The unsuitability (measurements may not be co-located) or unavailability (e.g., wind-speed) of measurements.

iv) Considerable progress has been achieved by the BSRN community and the ExTrac project, in moving the agenda forward on the submission of raw pyrgeometer data to the BSRN archive. At a recent BSRN meeting in June 2022, it was decided to phase-in the mandatory submission of this data in the near future. Logistical aspects are currently being discussed, and new guidelines will appear in a forthcoming update of the BSRN Technical Manual (Lanconelli et al., in preparation). While the results from our project are encouraging, obtaining the original raw data from station archives is still the preferred approach to deal with past, present and future raw data. Such an approach will require substantial efforts by most BSRN stations if raw data are still available but could be supported by the resources of the BSRN and WMO communities.

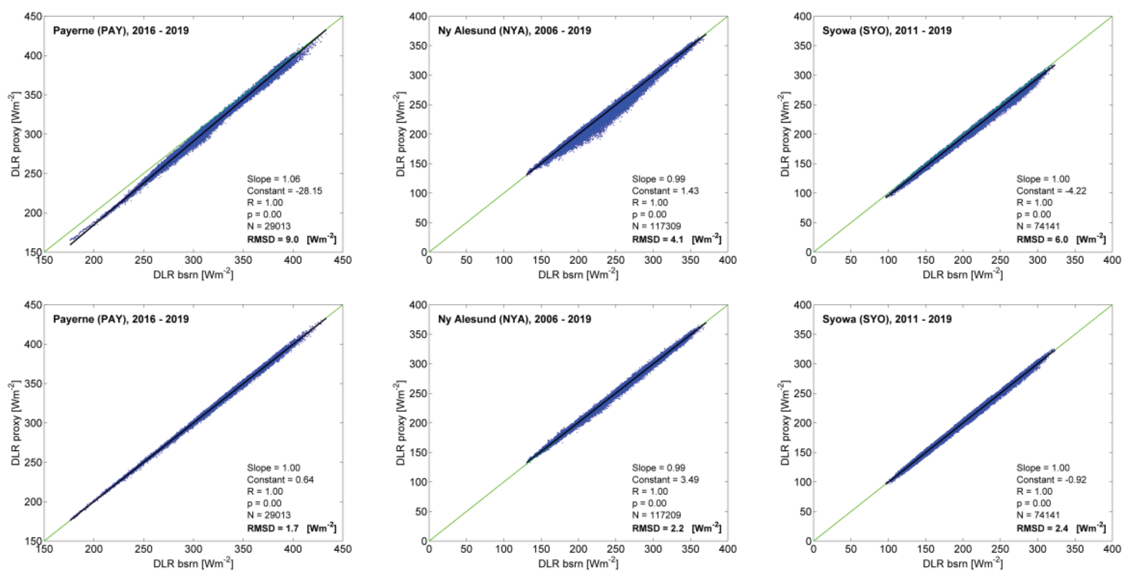

FIGURE 1. DLR_{proxy} vs DLR_{BSRN} (1-hr data) at BSRN stations. Top line, left to right: Basic model for PAY, NYA and SYO. Bottom line, left to right: Station-specific model for the same stations. Statistics and RMSD values are shown in each graph.

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