Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2017-28, 2017
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 2 May 2017
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The Global Energy Balance Archive (GEBA) version 2017: A database for worldwide measured surface energy fluxes

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Abstract. The Global Energy Balance Archive (GEBA) is a database for the central storage of the worldwide measured energy fluxes at the Earth's surface, maintained at ETH Zurich (Switzerland). This paper documents the status of the GEBA version 2017 dataset, presents the new web-interface and user access and reviews the scientific impact that GEBA data had in various applications. GEBA has continuously been expanded and updated and contains in its 2017 version around 2500 stations with 500‘000 monthly mean entries of various surface energy balance components. The database contains observations from 15 surface energy flux components, with the most widely measured quantity available in GEBA being the shortwave radiation incident at the Earth’s surface (“global radiation”). Many of the historic records extend over several decades. GEBA contains monthly data from a variety of sources, namely from the World Radiation Data Centre (WRDC) in St. Petersburg, from National Weather Services, from different research networks (BSRN, ARM, SURFRAD), from peer-reviewed publications, project and data reports, as well as from personal communications. Quality checks are applied to test for gross errors in the dataset. GEBA has played a key role in various research applications, such as in the quantification of the global energy balance, in the discussion of the anomalous atmospheric absorption or in the detection of multi-decadal variations in surface solar radiation, known as “global dimming” and “brightening”. GEBA is further extensively used for the evaluation of climate models and satellite-derived surface flux products. On a more applied level, GEBA provides the basis for engineering applications in the context of solar power generation, water management, agricultural production and tourism. GEBA is publicly accessible through the internet via www.geba.ethz.ch. Supplementary data are available at https://doi.org/10.1594/PANGAEA.873078.

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1 Introduction

Knowledge on the spatio-temporal distribution of the individual energy balance components at the Earth's surface is essential for the understanding of the genesis and evolution of Earth's climate. Such knowledge is also required for various practical applications in the sectors of renewable energies, agriculture, water management, or tourism. Surface energy fluxes are not directly measurable from space, as the associated signals reaching the satellite sensors are significantly perturbed on their transfer through the atmosphere. Correction of these atmospheric influences therefore requires the use of models or empirical relations, which induces uncertainties. Therefore direct measurements taken at the Earth's surface are essential as independent information source for the quantification of the surface energy fluxes. The monitoring of some of the surface energy fluxes, particularly shortwave radiation incident at the Earth's surface, started in the early 20th century at a small number of sites. More widespread measurements of the surface energy balance components were initiated in the International Geophysical Year (IGY, 1957/1958). Many of these historic measurements have been compiled in the Global Energy Balance Archive (GEBA) at ETH Zurich, whose 2017 version is described in the following.

2 History of GEBA

In the early 1980s, Atsumu Ohmura and collaborators at ETH Zurich started to systematically collect instrumentally observed data from any accessible source on directly measured monthly mean energy balance components at the Earth's surface around the world. These sources included data from monographs, periodicals, data reports, personal communications and published and unpublished manuscripts, which were initially stored on paper forms. In 1985, the data compilation included about 5000 energy flux values on such paper records. In 1986, this endeavor became a project of the World Climate Program – Water. To transfer the data collection into digital form, a database approach was chosen. The first version of the GEBA database was implemented in 1988, following the design of a relational database (Ohmura et al., 1989). In April 1991, the GEBA database was for the first time opened to the scientific community. In the subsequent years, GEBA has been steadily growing, as documented in reports on early versions of GEBA (Ohmura and Gilgen, 1991;Gilgen et al., 1997;Gilgen and Ohmura, 1999). In the GEBA version 1991, all flux data, collected in different units, were converted into the common unit Watts per square meter (Wm^{-2}) before storage. To facilitate the quality assessments and traceability of the data, in the GEBA version 1995 an additional internal table was implemented in the relational database, which contains the data also in their original units. In October 1997, GEBA became for the first time accessible through the internet. Since the retirement of Prof. Ohmura in 2007, the first-author of this paper has ensured the continuation of GEBA at ETH Zurich. The continuation of GEBA became possible through the technical support and maintenance of the database by the IT services of ETH Zurich from 2008 onward, which included also a complete renewal of the technical infrastructure.

As compared to the early documentations of GEBA in the 1990s, GEBA has undergone substantial changes in terms of available data, data access, and internet appearance, and has played a key role in major research activities, as outlined in the sections below.

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3 Content and data sources of GEBA

GEBA compiles monthly mean data from various energy fluxes observed at the Earth's surface, namely global radiation (i.e., total surface downward shortwave radiation, also known as surface solar radiation), diffuse and direct shortwave radiation, surface albedo and reflected shortwave radiation, longwave downward and upward radiation, radiation balance (surface net radiation), sensible and latent heat flux, subsurface heat flux, and latent heat of melt (see Table 1). GEBA contains strictly only directly measured surface energy fluxes, empirically derived fluxes are not considered.

Over the years, monthly mean surface energy flux data have been compiled from various sources, namely from the World Radiation Data Center (WRDC) in St. Petersburg, from the Baseline Surface Radiation Network (BSRN) (Ohmura et al., 1998), from the Atmospheric Radiation Measurement program (ARM) (Stokes and Schwartz, 1994), from the surface radiation (SURFRAD) network maintained by the National Oceanic and Atmospheric Administration (NOAA) (Augustine et al., 2000), from various periodicals, journal publications and data reports, from personal communications of unpublished data, and from individual weather services such as MeteoSwiss.

GEBA in its 2017 version contains 2500 worldwide distributed stations as shown in Figure 1, with about 500'000 monthly mean values (Table 1). By far the largest amount of data in GEBA refers to the surface downward shortwave radiation (Table 1).

Error estimates of these data and the quality checks applied are described in detail in Gilgen et al. (1998) and Gilgen and Ohmura (1999). All energy fluxes stored in the GEBA database are subject to a "physical sanity" check which requires the energy flux values to be within physically possible magnitudes (Gilgen and Ohmura, 1999). Most of the shortwave radiation measurements in GEBA were made with pyranometers. These measurements have instantaneous accuracy limitations of 3–5% of the full signal due to cosine response and thermal offset errors combined with other sources of uncertainty (Michalsky et al., 1999;Wild et al., 2013). Their accuracy in the field in terms of relative random measurement error has been estimated by Gilgen et al. (1998) at 5% of the monthly mean and 2% of the yearly mean values, based on comparisons of long-term pyranometer measurements of five pairs of nearby stations stored in GEBA. Diffuse shortwave radiation measurements are obtained by shading the pyranometers from the direct solar beam, with an instantaneous accuracy of 2 - 4 Wm^{-2} (Michalsky et al., 2007). The accuracy of downward longwave radiation measurements carried out with pyrgeometers is near 3 - 4 Wm^{-2} (Philipona et al., 2001;Marty et al., 2003;Wang and Dickinson, 2013a).

The longest record in GEBA comes from Stockholm and contains downward shortwave radiation observations exceeding 90 years back to 1922 (Figure 2). With its focus on monthly data, the GEBA dataset is designed for climatological applications. For energy flux data with higher temporal resolution, the reader is referred to other sources such as the database of the BSRN (http://bsrn.awi.de/), which provides surface radiation data at minute resolution.

4 Access to GEBA

GEBA is worldwide accessible through the internet. The official address of the GEBA version 2017 is www.geba.ethz.ch.

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Note that the address www.bsrnstatus.ch/gebastatus as given in older documentations is no longer valid. The GEBA version 2017 comes with a newly designed user interface and user administration tool. To grant access to the data, a registration is required, which can be achieved by filling in the respective form provided on the GEBA website. Thereon, also a specification of the intended usage of the data is required. It is the policy of GEBA that the data are available at no cost for bona fide research. The direct commercial use, i.e. selling of the data, is not allowed.

The new user interface allows the selection of the various energy balance components stored in GEBA as given in Table 1, as well as the period under consideration (Figure 3 left). It then further allows the selection of specific regions, countries or individual stations of interest (Figure 3 center / right). Based on this information, a database query is generated to process the retrieval of the desired selection. The user in return obtains 2 different files, one file containing the original energy flux data, and one file containing meta data in terms of station names, coordinates, station history with known changes in instrumentation, data evaluation procedures and data publication standards. The specification of the data formats of the two files can be found on the GEBA website in the “Data Formats” section under the “Data Retrieval” menu. As mentioned previously, GEBA internally stores all data in the original units as they were published, as well as converted into Wm^{-2}. All retrieved data that are delivered to the user are exclusively in Wm^{-2}, to facilitate their usage and avoid misinterpretation.

5 Research done with GEBA

GEBA data have been applied in numerous studies, and have contributed to a number of key scientific issues. In the following, we will review some of the achievements that have been obtained using GEBA data.

5.1 Estimation of the global energy balance

A major aim of GEBA since its initiation in the 1980s was the reevaluation of the global energy balance (Ohmura et al., 1989). A particular challenge thereby pose the energy fluxes at the Earth’s surface, which cannot be directly measured from space as they are obscured by the intermediate atmosphere, and which are accordingly afflicted with substantial uncertainties. Information from direct observations at the surface as provided by GEBA is therefore particularly valuable to constrain these fluxes. A first estimation of the geographical distribution of the individual surface energy balance components based on direct observations from GEBA was performed by Ohmura and Gilgen (1993), and updated in Ohmura and Raschke (2005). Wild et al. (1998b) used a combination of GEBA data and respective biases of a climate model to infer the magnitudes of the global mean energy balance components. For the fifth IPCC assessment report (AR5) they updated their global energy balance estimates using a similar methodology based on a comprehensive set of state of the art models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and their biases with respect to GEBA and BSRN stations (Wild et al., 2013) (Figure 4). The methodology allowed also the estimation of the Earth’s energy balance separately over land and oceans (Wild et al., 2015). All these evaluations have advocated a lower surface downward shortwave and

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higher downward longwave radiation than in some of the traditional estimates such as those used in the IPCC assessments up to the 4th report.

A particular aspect of the global energy balance, namely the quantification of the absorption of shortwave radiation in the atmosphere, has been an issue where GEBA data have contributed significantly over decades. In the early days of GEBA, it was debated whether estimates of shortwave atmospheric absorption may be too low due to an underestimated absorption in clouds, a phenomenon known as "anomalous cloud absorption". GEBA was of key importance to quantify the underestimation in atmospheric shortwave absorption and to relate it to a lack of absorption in the cloud-free atmosphere rather than in clouds (Li et al., 1995a;Wild et al., 1995). First attempts to estimate the shortwave atmospheric column absorption by combining surface observations from GEBA with collocated satellite observations of the Top-of-Atmosphere (TOA) fluxes from the Earth Radiation Budget Experiment (ERBE) were made in Wild et al. (1998b) and Wild (2000). More recently, with the advent of high quality TOA satellite observations from the Clouds and the Earth's Radiant Energy System (CERES) program, CERES rather than ERBE data have been combined with GEBA data to improve the quantification of the atmospheric shortwave absorption (Hakuba et al., 2014b). To estimate potential uncertainties induced by the scale mismatch between the gridded 1° TOA satellite data from CERES and the surface point observations from GEBA, the representativeness of the GEBA sites for their larger scale surroundings has been thoroughly assessed (Hakuba et al., 2013;Hakuba et al., 2014a). Based on the collocated GEBA and CERES observations, the atmospheric shortwave absorption over Europe has been estimated by Hakuba et al. (2014b) at 23% of the TOA insolation. The 23% were shown to be largely invariant with respect to latitude and season (Hakuba et al., 2014b;Hakuba et al., 2016), and in line with recent global estimates (Wild et al., 2013;Wild et al., 2015). Globally it has been estimated that the absorption of shortwave radiation in the climate system (70% of the TOA insolation) occurs to 1/3 in the atmosphere and to 2/3 at the Earth's surface (Wild et al., 2015).

5.2 Detection of decadal changes in the surface energy fluxes

GEBA has played a key role in the discovery that the downward shortwave radiation at the Earth's surface has not been stable over the years, but underwent substantial multidecadal variations (see Figure 2 as an illustrative example). Based on European GEBA sites, Ohmura and Lang (1989) for the first time identified a downward trend in this component from the 1950s to the 1980s, a phenomenon that later became known as "global dimming" (Stanhill and Cohen, 2001). Follow-up studies found similar tendencies at GEBA sites around the world (e.g., Gilgen et al., 1998;Liepert, 2002;Wild, 2009 and references therein). When updating the GEBA records into the 2000s, Wild et al. (2005) noted a trend reversal during the 1980s and widespread recovery from previous dimming, which they coined "brightening" (cf. Figure 2). Chiacchio and Wild (2010) pointed out that the dimming and subsequent brightening at the European GEBA sites is particularly evident in spring and summer. The longest records in GEBA further indicate an increase in downward shortwave radiation in the 1930s and 1940s, which has been termed "early brightening" (Ohmura, 2006, 2009;Wild, 2009) (cf. Figure 2).

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Norris and Wild (2007) and Norris and Wild (2009) used the GEBA data and a satellite-derived regression method to estimate the effects of changes in cloud cover on dimming and brightening. Their results suggest that changes in cloud cover can hardly explain the observed decadal variations in surface shortwave radiation, pointing to other important influential factors, particularly changes in aerosols and/or changes in cloud optical properties. It has also been controversially discussed to what extent the dimming and brightening trends in GEBA may have been subject to urbanization effects (Alpert et al., 2005;Wang et al., 2014;Imamovic et al., 2016).

A comprehensive assessment of the trends in Europe using homogeneous GEBA records is reported in Sanchez-Lorenzo et al. (2015). Figure 5 shows an updated composite mean series of the 56 European GEBA records used in Sanchez-Lorenzo et al. (2015) and illustrates the sequence of “early brightening”, “dimming”, and “brightening” over Europe. A long-term diffuse radiation record from the station Toravere (Estonia) contained in GEBA is displayed in Figure 6. The diffuse radiation shows opposite tendencies compared to Figure 5, with an increase in the dimming period up to the mid-1980s, in line with enhanced scattering from aerosols and/or clouds in this period, and a subsequent decrease in the brightening period with declining aerosol and/or cloud scattering.

GEBA data have also been used to infer long-term trends in the non-radiative surface energy flux components, particularly latent heat (evapotranspration). Ohmura and Lang (1989) noted that decadal changes of evapotranspiration run in parallel to the fluctuation in surface shortwave radiation. Wang et al. (2010) used shortwave radiation data from GEBA to reconstruct terrestrial evapotranspiration trends and showed that they undergo significant decadal variations.

5.3 Validation of surface energy fluxes from climate models, reanalyses and satellite products

A major application of the GEBA dataset has always been its usage as ground-truth and benchmark for the assessment of calculated gridded surface flux fields from climate models, satellite products and reanalyses. GEBA data allowed the identification of major biases and weaknesses in these various products of surface energy flux estimates.

A first evaluation of the global surface radiation fields simulated by climate models with direct surface observations is documented in Wild et al. (1995), which revealed an overestimated downward shortwave radiation due to an overly transparent atmosphere in these models, and an underestimated downward longwave radiation on a climatological mean basis. These biases turned out to be long-standing issues in many climate models up to the present day. Numerous assessments as reviewed in Wild (2008) underline the importance of GEBA as a primary reference dataset for radiative flux evaluation in global and regional climate models. GEBA-based evaluations of the radiation climatologies of the latest generation of climate models (CMIP5) used in the 5^{th} IPCC assessment report (AR5) have been presented in several studies (Wild et al., 2013;Wild et al., 2015;Ma et al., 2015;Bartok et al., 2017). Figure 7 illustrates the large spread of the biases in downward shortwave radiation fluxes simulated by more than 40 CMIP5 models when compared to an average over 760 sites from GEBA, covering almost 40 Wm^{-2}, and documents the overestimation of these fluxes in many of the models.

Also the non-radiative surface energy balance data contained in GEBA have been used for the evaluation of the model climatologies. For example, the surface albedo measurements have been used to assess the simulation of snow albedo in a global climate model (Roesch et al., 1999), and the sensible and latent heat fluxes in GEBA have been instrumental to assess these turbulent fluxes in climate models (Wild et al., 1996;Sheppard and Wild, 2002).

Apart from the assessment of the simulated climatological mean fields, a number of studies used GEBA data also to assess the climate model-simulated trends particularly in the shortwave radiation in the context of the dimming and brightening phenomenon. These studies show that climate models typically do not fully reproduce the strong multidecadal variations seen in the GEBA data (Ruckstuhl and Norris, 2009;Wild and Schmucki, 2011;Zubler et al., 2011;Allen et al., 2013;Bartok et al., 2017). The inadequate representation of decadal changes in aerosols has been suggested as a potential cause for the lack of trends in the simulated surface downward shortwave radiation fields. In contrast, Nabat et al. (2014) were able to adequately reproduce the brightening trends at the GEBA sites over Europe with a regional climate model and a newly compiled dataset on the historic aerosol evolution. While this regional climate model took into account the direct, semi-direct and first indirect aerosol effects, the simulated brightening was dominated by the direct effect. Folini and Wild (2015) showed that the climate model ECHAM5-HAM with sophisticated treatment of interactive aerosols and emissions from the Japanese National Institute for Environmental Studies (NIES) overall reproduced the magnitude of the recorded trends in China as given in GEBA. GEBA data have not only been used to assess the trends of (total) surface downward shortwave radiation, but also of its direct and diffuse components (Mercado et al., 2009).

GEBA data further have extensively served as ground-truth for surface radiative fluxes derived from satellites and reanalyses. The earliest investigations that used GEBA data to assess satellite-derived surface fluxes were made by Whitlock et al. (1995), Rossow and Zhang (1995), and Li et al. (1995b). Hatzianastassiou et al. (2005), based on their global satellite-derived surface radiation product validated against GEBA data, provided additional evidence for a lower downward shortwave radiation than commonly assumed, in line with the findings of the GEBA-based global energy balance studies mentioned above. A detailed assessment of their radiation scheme compared to GEBA data over the Mediteranien area was performed by Papadimas et al. (2012) and Pyrina et al. (2015). Hatzianastassiou et al. (2012) further noted that the trends in their surface shortwave radiation product are in reasonable agreement with the GEBA records. An assessment of the Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB) product with GEBA data can be found in Hinkelman et al. (2009) and Zhang et al. (2009). The most recent assessment of surface downward shortwave radiation as provided by four different global satellite products based on GEBA data is documented in Zhang et al. (2015). Over the region covered by the geostationary METEOSAT disk, the surface radiative flux products of the Satellite Application Facility on Climate Monitoring (CM-SAF) were extensively validated against GEBA observations (Krahenmann et al., 2013;Sanchez-Lorenzo et al., 2013;Muller et al., 2015;Alexandri et al., 2017;Sanchez-Lorenzo et al., 2017). These studies have also assessed the temporal stability of the satellite-derived surface shortwave radiation against GEBA records, especially over Europe A comparison of trends of a composite of 47 European GEBA time series with the corresponding composite of the satellite-derived time series from the Satellite Application Facility on Climate Monitoring (CM-SAF) is shown in Figure 8 (adapted from Sanchez-Lorenzo et al., 2017).

The earliest assessment of reanalysis fluxes using GEBA data is documented in Wild et al. (1998a), while the most up to date assessment of six recent reanalyses has been performed by Zhang et al. (2016). Similarly to climate models, reanalyses were shown to have difficulties in representing the multidecadal variations in surface shortwave radiation seen in the GEBA data (Wild and Schmucki, 2011). The quality of reanalysis-calculated surface radiative fluxes has also been assessed with GEBA data to check their suitability as input data in a global hydrological modeling framework (Müller Schmied et al., 2016).

In summary, GEBA continues to play a major role in the assessment of surface energy fluxes in climate models, satellite-derived products and reanalyses. Overall, in many satellite-derived and reanalysis products the comparisons with GEBA data revealed a tendency to overestimate the absolute magnitude and underestimate the trends in surface shortwave radiation compared to the ground-based observations. This has been partially related to the use of inadequate representations of aerosols and a lack in their temporal variation.

5.4 Constraining radiative forcings

GEBA data have also been useful to constrain historic radiative forcings, particularly from aerosols, and thereby contributed to the estimation of the climate sensitivity. Improved knowledge of the evolution of aerosol forcing since preindustrial times, combined with the observed global warming and estimated greenhouse gas forcing over this period allows to better constrain the Earth's climate sensitivity. Storelvmo et al. (2016) used the GEBA data as an indicator of the historic evolution of the aerosols, which lead to an estimation of a comparatively high transient climate sensitivity at 2.0±0.8K entirely based on observational records, using a statistical approach usually applied to economic time series. The transient climate sensitivity refers to the global mean warming at the time of a doubling of the CO_2 concentration.

Cherian et al. (2014) noted that the brightening trend over Europe in several climate models scales well with the regional and global mean effective forcing by anthropogenic aerosols ("present-day" minus "preindustrial"). Using the observed brightening trend from European GEBA sites as constraint, this enabled to infer a global mean total aerosol effective forcing of about −1.30 Wm^{-2}.

5.5 Implications for climate change and applied studies

Potential implications of the variations in surface radiation as discovered in the GEBA data for different aspects of climate change have been investigated in numerous studies. These include for example their implications for evaporation changes (Wang et al., 2010), for changes in the intensity of the global water cycle (Wild, 2012), for global warming and diurnal temperature range (Wild et al., 2007;Makowski et al., 2009;Wang and Dickinson, 2013b), for changes in isoprene emissions (Stavrakou et al., 2014) and for glacier melt (Ohmura et al., 2007;Huss et al., 2009). Further, GEBA data were used for the assessment of the worldwide variation of diffuse and direct shortwave radiation of relevance for biosphere growth, agricultural production, and tree-ring density (Mercado et al., 2009;Wild et al., 2012;Stine and Huybers, 2014).

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On a more applied level, GEBA provides data for the assessment of the resources available for solar power production (Müller et al., 2014), and serves as data base for the software package Meteonorm developed by the company Meteotest, which delivers worldwide information on various aspects of shortwave irradiances for applications in the area of photovoltaic and solar thermal power production as well as building simulations.

6 Summary

The Global Energy Balance Archive (GEBA), with its variety of surface energy balance parameters and long-term historical records, contains a unique data collection of worldwide measured surface energy fluxes on a monthly basis to serve the scientific community. GEBA allows the central and uniform storage of the vast number of energy flux measurements from heterogeneous sources that have been performed over the past decades by a multitude of organizations and individuals, such as under the auspices of National Meteorological services, agricultural or environmental agencies or during expeditions and field campaigns. This manuscript describes the GEBA version 2017 and the updates that this data archive has undergone since its last documentation in the 1990s, in terms of its data content, its worldwide access through a newly designed web-interface as well as its new internet address, and highlights some of the research that has been made based on GEBA. GEBA has played a key role in the detection of the phenomenon of global dimming and brightening, in the quantification of the Earth's surface energy budget and atmospheric absorption, in the detection of biases in surface energy fluxes from climate models, reanalyses and satellite-derived products, in the determination of the observation-based transient climate sensitivity and aerosol radiative forcing, as well as in assessments of solar resources for solar power production. It is expected that GEBA will continue to state a key information source on instrumentally measured surface energy fluxes in support of the abovementioned and novel research directions in the future.

Acknowledgement. We are indebted to the IT services at ETH Zurich for their technical support of the GEBA Oracle database and related issues over many years, particularly to Bengt Giger, Swen Vermeul, Benno Luthiger and Matteo Corti for their hands-on work on the GEBA database, web-interface, and user administration tool. Barbara Trüssel, Stefanos Mystakidis, Pavle Arsenovic, and Mijung Song are highly acknowledged for their work on data acquisition for GEBA. Particular thanks go also to Hans-Heini Vogel and Urs Beyerle for their support of the transition of the GEBA web-interface into the new web content management system AEM. A special thank goes to Hans Gilgen for his efforts to design and manage the GEBA database over many years. We are grateful to Rainer Sieger for his unbureaucratic inclusion of the data in PANGAEA. Barbara Schär designed the energy balance diagram shown in Figure 4. Arturo Sanchez-Lorenzo was supported by a postdoctoral fellowship JCI-2012-12508 and project CGL2014-55976-R financed by the Spanish Ministry of Economy and Competitiveness. We greatly acknowledge also all observers that are out in the field making all the precious measurements that GEBA relies on.

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Table 1. List of the various energy balance components included in GEBA, with the number of stations measuring each component, the number of monthly values included, and the earliest year that has data for each component.

Energy Balance Component	*#Sites*	*#Monthly means*	*First year measured*
Global radiation	2249	357583	1919
Direct solar radiation	109	9553	1934
Diffuse solar radiation	787	70069	1950
Albedo	510	3839	1954
Reflected short-wave radiation	97	5827	1954
Long-wave incoming radiation	83	3984	1954
Long-wave outgoing radiation	48	1659	1954
Long-wave net radiation	30	735	1959
Radiation balance	709	25392	1954
Sensible heat flux	62	250	1980
Latent heat flux	75	686	1980
Subsurface heat flux	61	481	1968
Latent heat of melt	20	59	non-permanent
Ultraviolet radiation	10	242	1976
Other component	81	26814	1957
absorbed global radiation	32	1609	1947
outgoing short + longwave rad	2	24	1959
latent and sensible heat flux	2	21	1976
Circumglobal radiation	4	501	1958

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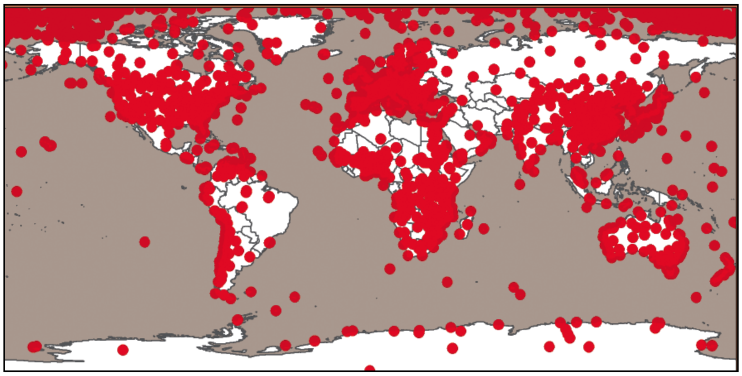

Figure 1. Distribution of the worldwide observation sites available in GEBA.

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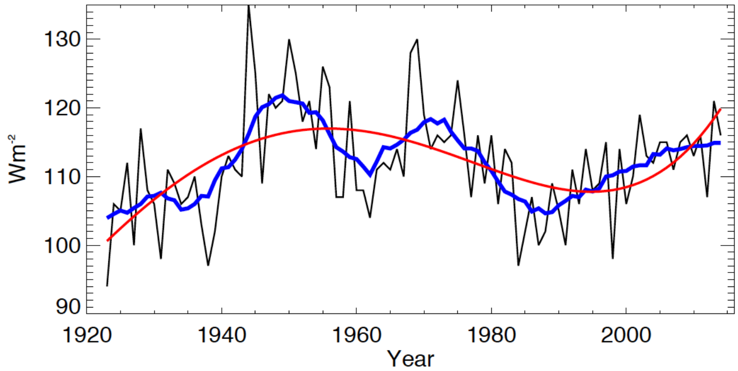

Figure 2. The longest continuous record available in GEBA: surface downward shortwave radiation measured in Stockholm since 1922. Five year moving average in blue, 4th order regression model in red. Units Wm^{-2}. Substantial multidecadal variations become evident, with an increase up to the 1950s ("early brightening"), an overall decline from the 1950s to the 1980s ("dimming"), and a recovery thereafter ("brightening").

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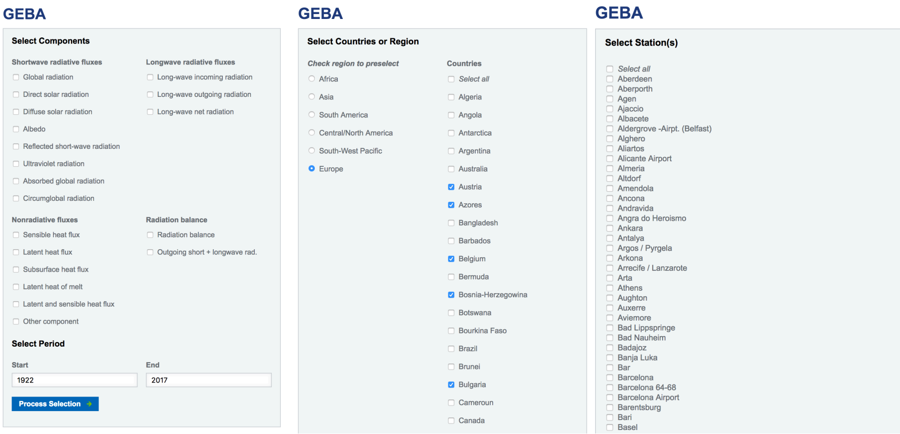

Figure 3. Extract from the new GEBA web interface at www.geba.ethz.ch. The web interface allows the selection of a variety of surface energy balance components, the period to be retrieved, and the region, country or specific stations of interest.

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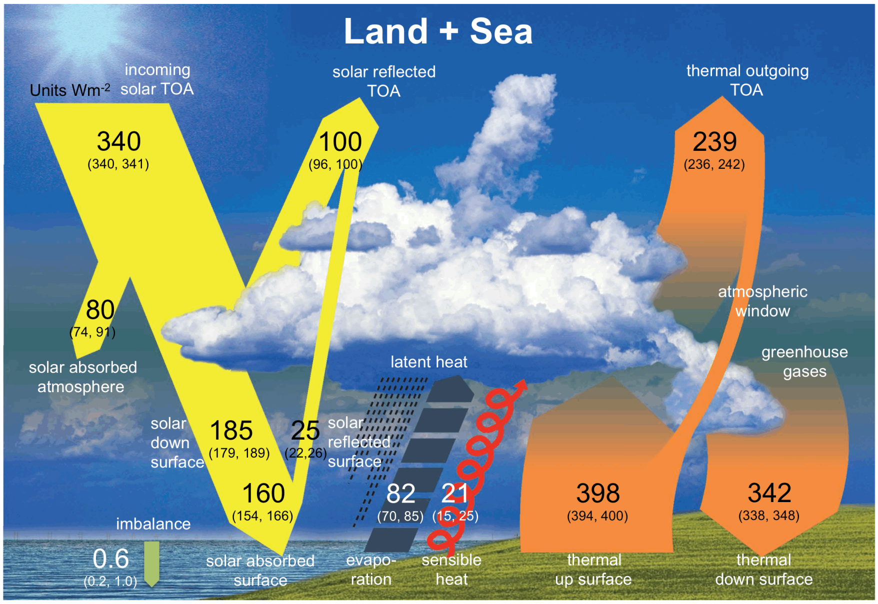

Figure 4. Schematic diagram of the global mean energy balance of the Earth. Numbers indicate best estimates for the magnitudes of the globally averaged energy balance components together with their uncertainty ranges in parentheses, representing present day climate conditions at the beginning of the 21th century. Top of atmosphere fluxes determined from the CERES satellite observations. Surface radiative flux estimates derived from the CMIP5 model bias structure with respect to GEBA and BSRN observations as outlined in Wild et al. (2013) and Wild et al. (2015). Units Wm^{-2}. Adapted from Wild et al. (2015).

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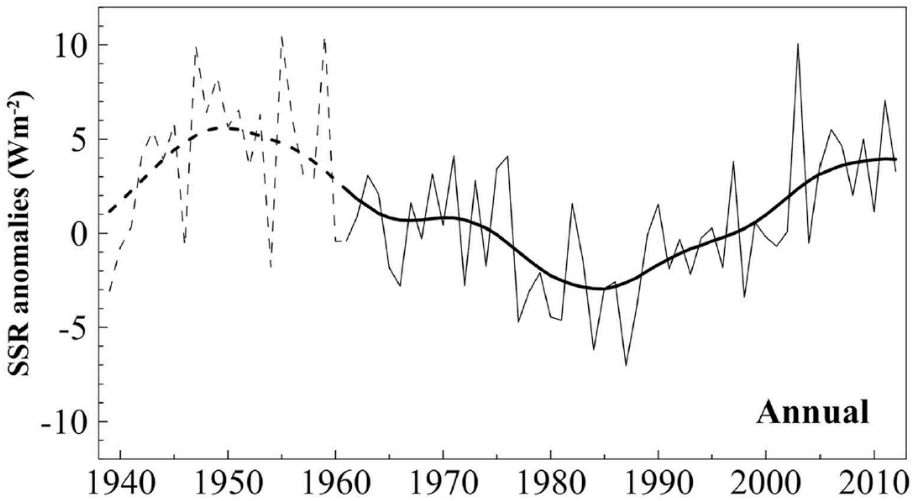

Figure 5. Composite of 56 European GEBA time series of annual surface downward shortwave radiation (thin line) from 1939 to 2013, plotted together with a 21 year Gaussian low-pass filter (thick line). The series are expressed as anomalies (in Wm^{-2}) from the 1971–2000 mean. Dashed lines are used prior to 1961 due to the lower number of records for this initial period. Updated from Sanchez-Lorenzo et al. (2015) including data until December 2013.

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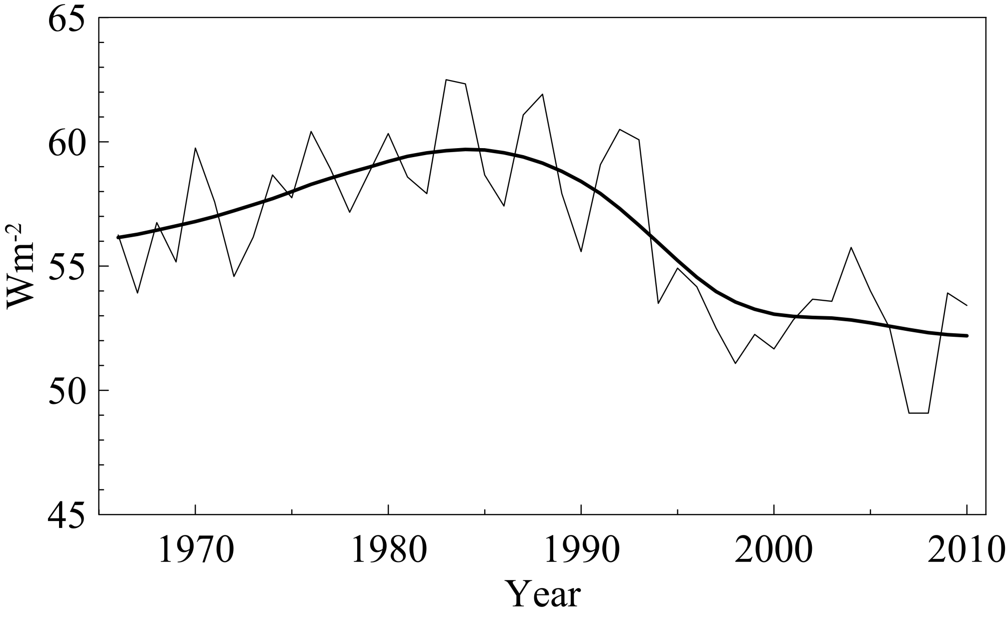

Figure 6. Long term annual mean diffuse radiation record from 1966 to 2010 (thin line) plotted together with a 21 year Gaussian low-pass filter (thick line) measured at the station Toravere (Estonia) contained in GEBA.

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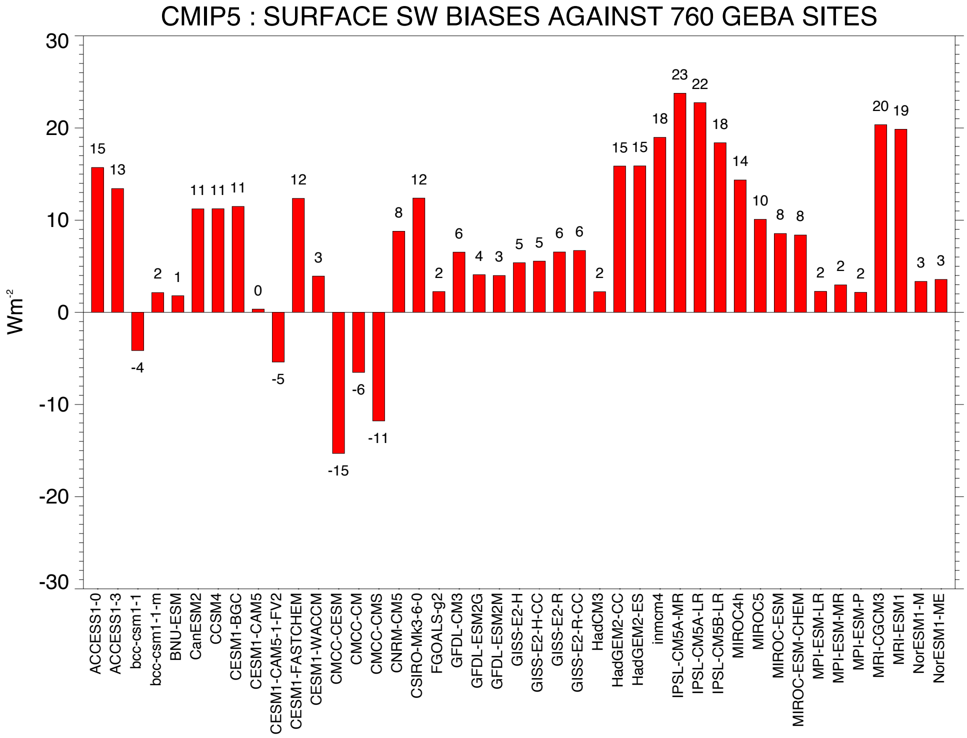

Figure 7. Average biases (model – GEBA observations) in surface downward shortwave radiation at Earth's surface calculated in 43 different CMIP5 climate models averaged over 760 sites from GEBA. Units Wm^{-2} (from Wild et al., 2015).

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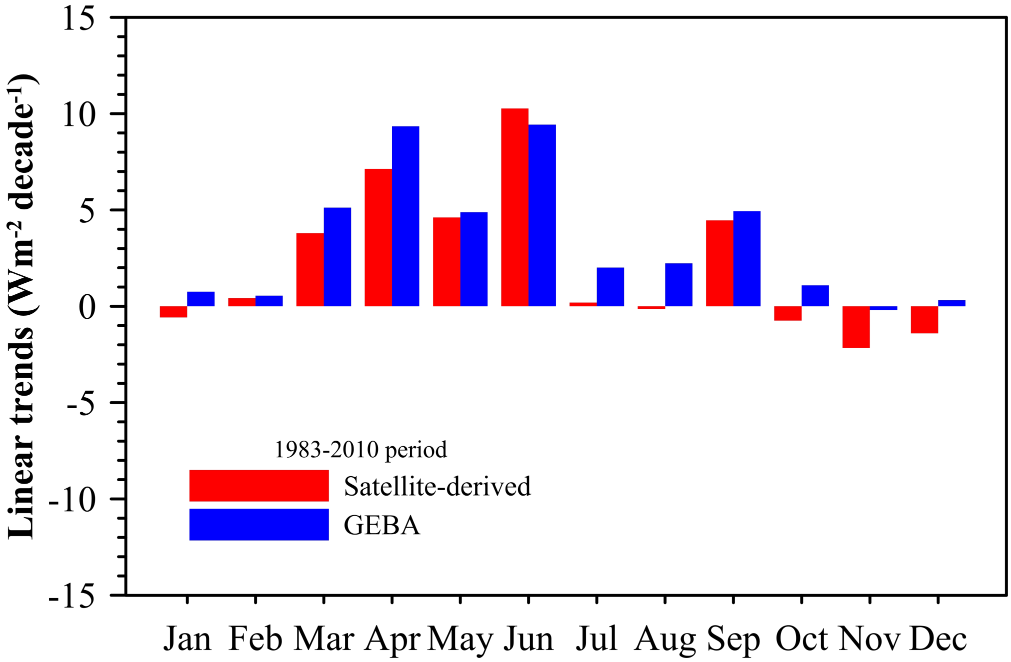

Figure 8. Linear trends of the mean monthly time series obtained as composite from 47 GEBA station records and collocated satellite-derived records from CM-SAF over Europe over the period 1983 - 2005. Units in Wm^{-2} per decade (adapted from Sanchez-Lorenzo et al., 2017).