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A New Diagram of the Global Energy Balance

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Abstract. Here we provide a new assessment of the global mean energy fluxes from a surface perspective and present an associated diagram of the global mean energy balance, adapted from the study by Wild et al. (2013) [1] with two slight modifications as outlined in this paper. The radiative energy exchanges between Sun, Earth and space are now accurately quantified from new satellite missions. Much less has been known about the magnitude of the energy flows within the climate system and at the Earth surface, which cannot be directly measured by satellites. In addition to satellite observations, we make extensive use of the growing number of surface observations to constrain the global energy balance not only from space, but also from the surface. We combine these observations with the latest modeling efforts performed for the 5th IPCC assessment report to infer best estimates for the global mean surface radiative components. Our analyses favor global mean downward surface solar and thermal radiation values near 185 and 342 Wm^{-2}, respectively, which are most compatible with surface observations. Combined with an estimated surface absorbed solar radiation and thermal emission of 161 Wm^{-2} and 398 Wm^{-2}, respectively, this leaves 105 Wm^{-2} of surface net radiation available for distribution amongst the non-radiative surface energy balance components. Considering an imbalance of 0.6 Wm^{-2}, the global mean sensible and latent heat fluxes are estimated at 20 and 84 Wm^{-2}, respectively, to close the surface energy balance. The global mean surface radiative fluxes derived here in combination with a latent heat flux of 84 Wm^{-2} may be able to reconcile currently disputed inconsistencies between energy and water cycle estimates. The findings of this study are compiled into a new global energy balance diagram.

Keywords: Global energy balance, Earth radiation budget, IPCC-AR4, CMIP5.
PACS: 92.60.Ry, 92.60.Vb, 92.70.Mn.

INTRODUCTION

Earth's climate is largely regulated by the global energy balance, which considers the energy flows within the climate system and their exchanges with outer space. Iconic diagrams illustrating the global mean energy balance are prominently featured in many publications and textbooks. However, the actual numbers attached to the energy flows in the various diagrams show considerable differences [1-6]. This points to a major uncertainty in our understanding of the climate system, inherent in the quantification of some of these fundamental energy flows.

While the flows in and out of the climate system at the top of atmosphere (TOA) are now well determined form advanced space-born observation systems [7, 8], much less is known about the energy flows within the climate system and at the Earth's surface, which are not directly measurable from satellites. Uncertainties in the energy flows at the surface are thus generally larger than at the top of atmosphere, and therefore subject to greater debates.

In this respect, Ohmura [9] and Wild [5, 10] have been arguing over the past two decades that the global mean solar radiation reaching the Earth's surface should be lower than given in many estimates, including those published in the IPCC reports and calculated in climate models. On the other hand, Ohmura [9] and Wild [5, 10] also pointed out since the early 1990s that the atmospheric emission of thermal radiation down to the Earth's surface (downward thermal radiation) is too low in many of these estimates, which applies again also for the ones given in the IPCC reports as well as in many climate models (cf. also [6]).

In Wild et al. (2013) [1] we revisit this issue and make, in addition to satellite measurements, extensive use of the latest update of the growing number of surface observations. This allows to provide better constraints for the global energy balance not only from space, but also from the surface. We combine these observations with the latest modeling efforts performed for the 5th IPCC assessment report to infer best estimates for the global mean surface radiative components (see following section). We use these estimates together with the latest accepted values for the TOA exchanges from recent satellite programs, to derive a new diagram (shown here as Figure 2) representative for the global mean energy balance under present day climate conditions at the turn of the millennium.

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DATA USED IN THIS STUDY

The satellite observations to constrain the net fluxes at the TOA stem from the CERES mission that measures filtered radiances in the solar, total, and window regions [8]. The global mean estimates for the components of the TOA radiation budget are based on the Energy Balanced and Filled (EBAF) data set for the period 2001–2010 as part of the CERES mission, version EBAF 2.6r [11]. This data set adjusts the solar and thermal TOA fluxes within their range of uncertainty to be consistent with independent estimates of the global heating rate based upon in-situ ocean observations [8].

The surface observations to constrain the surface radiative fluxes are retrieved from two data sources: The Global Energy Balance Archive (GEBA [12]) and the database of the Baseline Surface Radiation Network (BSRN [13]). GEBA is a database for the worldwide measured energy fluxes at the Earth's surface and currently contains 2500 stations with 450‘000 monthly mean values of various surface energy balance components, maintained at ETH Zurich. By far the most widely measured quantity is the solar radiation incident at the Earth’s surface, referred to as downward solar radiation in the following. A subset of 760 GEBA sites, which provide multiyear records and allow the construction of representative solar radiation climatologies, was used in the present study. Further, a small set of records of downward thermal radiation contained in GEBA is used in this study. BSRN provides radiation measurements with high accuracy and temporal resolution (minute data). First BSRN sites became operational in the early 1990s. To date more than 50 anchor sites in various climate regimes have reported their data to the BSRN Archive at the Alfred Wegener Institute (http://www.bsrn.awi.de/). Further, we make use of general circulation model (GCM) calculated radiative fluxes that have been compiled in the framework known as CMIP5 (5th phase of the Coupled Model Intercomparison Project). These data have been organized by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for the 5th IPCC assessment report. We focus on “historical“ experiments and the turn of the millennium therein. These experiments were aimed at reproducing the climate evolution of the 20th century as accurately as possible, by considering all major natural and anthropogenic forcings, such as changes in atmospheric greenhouse gases, aerosol loadings, solar output, and land use. We further use the ERA40 reanalysis as an additional data source of simulated radiative fluxes.

BEST ESTIMATES FOR THE GLOBAL MEAN SURFACE RADIATIVE FLUXES

To obtain a best estimate for the globally averaged downward solar radiation, in [1] we compare, for 22 CMIP5 models and ERA40, their biases as calculated on average at 760 globally distributed sites from GEBA with their respective global mean values of downward solar radiation (Figure 1 left). In this Figure, each cross represents a climate model, with its mean bias in downward solar radiation compared to the 760 surface sites from GEBA on the horizontal axis, and its respective global mean value on the vertical axis. A clear tendency can be seen that models, which show a stronger overestimation of insolation at the surface sites, also tend to have a higher global mean insolation (correlation coefficient 0.80). The linear regression displayed in Figure 1 (left) between the model biases and their respective global means is significant at the 95% level. A best estimate for the global mean downward solar radiation can be inferred from the linear regression at the intersect where the bias against the surface observations becomes zero (indicated by the dashed lines in Figure 1). This way, a best estimate for the globally averaged downward solar radiation at Earth’s surface of 184.6 (±1.0) Wm^{-2} is obtained. To test the robustness of this estimate, we repeated the analyses using 44 worldwide distributed sites from BSRN instead of the 760 sites from GEBA to calculate the average model biases, and obtained very similar results [1]. The same approach is used in Figure 1 (right) to obtain a best estimate for the downward thermal radiation. This Figure shows the model simulated global means in downward thermal radiation as function of their biases averaged over 41 BSRN sites. A significant linear regression can be noted between the model biases and their global mean values, with a correlation of as high as 0.94. There is a clear tendency that the more a model underestimates the downward thermal radiation at the BSRN sites, the lower is also its global mean value. The zero model bias corresponds to a global mean downward thermal radiation of 342.3 (±0.5) Wm^{-2}, which is considered as best estimate in this framework. Also this estimate was shown to be robust with respect to differing surface based datasets [1].

Note that both global mean downward solar and thermal radiation estimates derived from Figure 1 coincide within 2 Wm^{-2} with latest satellite-derived estimates [14], which are completely independently determined. This amazing consistency provides further confidence in these new estimates for the global mean surface fluxes.

Figure 1 also demonstrates that most CMIP5 model overestimate the downward solar and underestimate the downward thermal radiation, a long-standing problem in climate models [5].

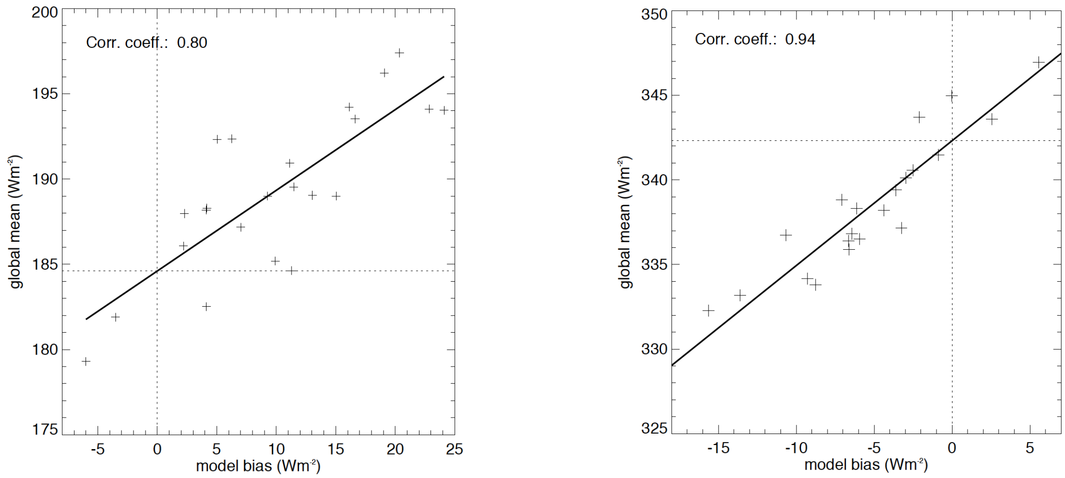

FIGURE 1. Left: Global mean surface downward solar radiation of 22 CMIP5 models and ERA40 versus their respective biases averaged over 760 surface observation sites from GEBA. A "best estimate" for the global mean downward solar radiation is inferred at the intersect between the linear regression line and the zero bias line (dotted lines). Units Wm^{-2}. Right: as left, but for downward thermal radiation and 41 observation sites from BSRN. Figures reproduced from Wild et al. 2013 [1].

A NEW DIAGRAM OF THE GLOBAL ENERGY BALANCE

The estimates derived above for the downward surface radiative fluxes are incorporated into a new global energy balance diagram in Figure 2, along with recent best estimates for the other energy balance components, representative for conditions at the beginning of the 21th century. This diagram corresponds to Figure 1 in [1] with some slight modification as outlined further below. We use for the TOA components in Figure 2 the recent estimate of 340 Wm^{-2} for the solar irradiance based on SORCE, with a rounded uncertainty range from 340 to 341 Wm^{-2} [15], for the reflected solar radiation the estimate from CERES EBAF of 100 Wm^{-2} (2-sigma uncertainty range from 96 to 100 Wm^{-2}) [8], and for the outgoing thermal radiation the CERES EBAF estimate of 239 Wm^{-2} (2-sigma uncertainty range from 236 to 242 Wm^{-2}) [8]. The difference between the net absorbed solar radiation, which amounts to 240 Wm^{-2}, and the 239 Wm^{-2} outgoing thermal radiation takes into account in a rounded way the approx. 0.6 Wm^{-2} global energy imbalance inferred from ocean heat content measurements.

For the surface fluxes in Figure 2, global mean downward surface solar and thermal radiation values near 185 and 342 Wm^{-2} are used, respectively, as derived above in Figure 1. For a discussion of the associated uncertainty ranges see [1]. We further use a global mean surface albedo of 0.13 to derive a global mean surface absorbed solar radiation of 161 Wm^{-2}. Compared to the diagram given in [1] we made two slight adjustments in Figure 2. Firstly, we marginally enhanced the best estimate for the global mean upward surface thermal radiation from 397 Wm^{-2} to 398 Wm^{-2}, to take into account latest estimates from satellite-derived products and reanalyses [2, 14, 16]. This results in a slightly lower global mean surface net radiation (105 Wm^{-2} compared to 106 Wm^{-2} in [1]) and latent heat flux (84 Wm^{-2} compared to 85 Wm^{-2} in [1]). Secondly, we adjusted the uncertainty range of the global mean latent heat flux to take into account constraints from corresponding global precipitation estimates given in the Global Precipitation Climatology Project (GPCP [17]). This range extends now from 70 Wm^{-2}, corresponding to the lower bound given in GPCP [17], up to 85 Wm^{-2} considered in [4] as upper limit of current uncertainties in precipitation retrieval. The latent heat flux of 84 Wm^{-2} required to close the surface energy balance in Figure 2 is thus at the upper end of the uncertainty range given by GPCP. On the other hand, [2] argue that GPCP precipitation estimates may be biased low and that accordingly the latent heat flux could be considerably higher. In light of this controversy on the magnitude of the global mean latent heat flux and associated precipitation, we consider the 84 Wm^{-2} in Figure 2 as a well-balanced estimate, as it is consistent with our best estimate for the available radiative energy at the surface, and still within the uncertainty of current global precipitation retrieval. Thus, the combination of surface radiative and latent heat flux estimates portrayed in Figure 2 may be able to reconcile currently disputed inconsistencies between energy and water cycle estimates (for more details on this debate see [1, 2, 4, 6]). This leaves around 20 Wm^{-2} for the sensible heat flux in Figure 2, considering the surface net radiation and latent heat flux of 105 and 84 Wm^{-2}, plus an imbalance of (rounded) 1 Wm^{-2}. The sensible heat flux shows the largest relative uncertainties, since it is the energy flux which is least constrained by observations.

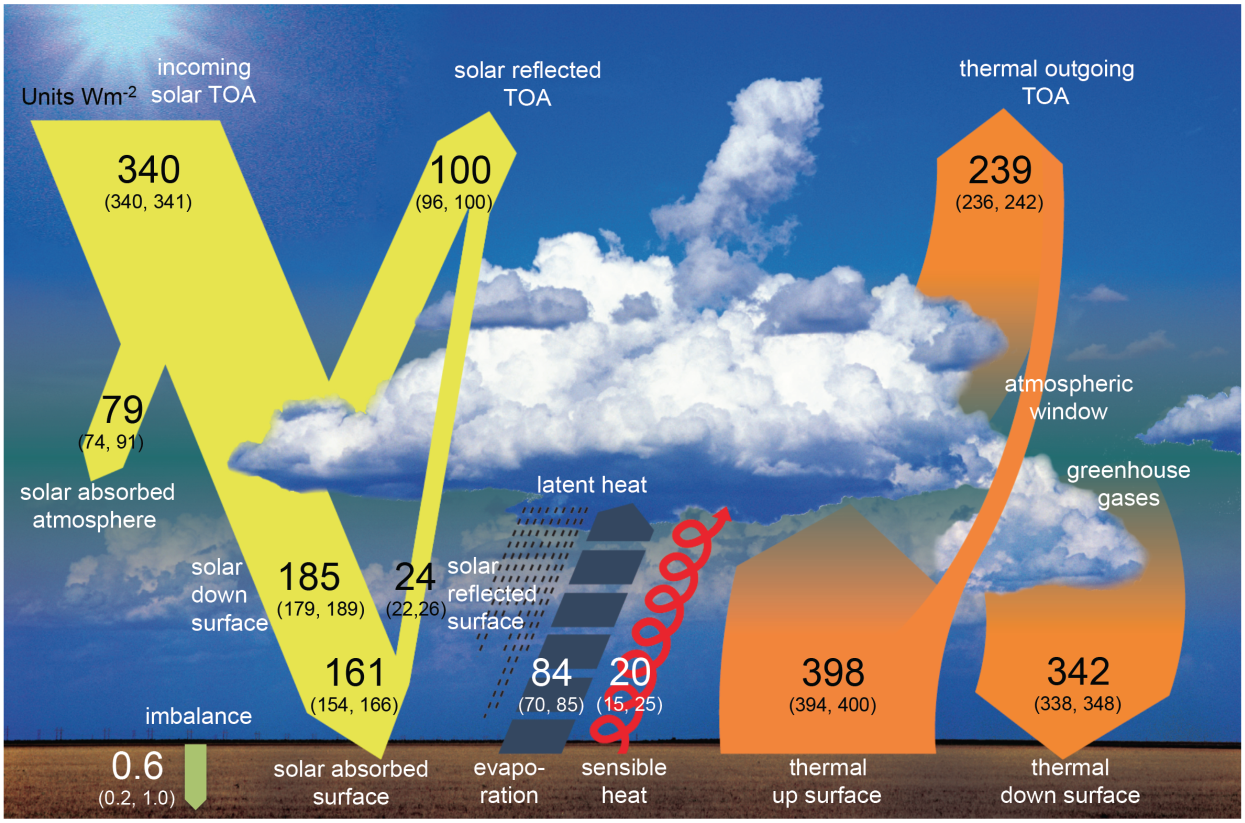

FIGURE 2. Schematic diagram of the global mean energy balance of the Earth. Numbers indicate best estimates for the magnitudes of the globally averaged energy balance components together with their uncertainty ranges, representing present day climate conditions at the beginning of the 21th century. Units Wm^{-2}. Figure adapted from Wild et al. (2013) [1] with slight modifications as outlined in the text.

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