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Cloud Effects on Atmospheric Solar Absorption in Light of Most Recent Surface and Satellite Measurements

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Abstract. At 36 locations worldwide, we estimate the cloud radiative effect (CRE_{atm}) on atmospheric solar absorption (ASR_{atm}) by combining ground-based measurements of surface solar radiation (SSR) with collocated satellite-derived surface albedo and top-of-atmosphere net irradiance under both all-sky and clear-sky conditions. To derive continuous clear-sky SSR from Baseline Surface Radiation Network (BSRN) in-situ measurements of global and diffuse SSR, we make use of the Long and Ackerman (2000) algorithm that identifies clear-sky measurements and empirically fits diurnal clear-sky irradiance functions using the cosine of the solar zenith angle as the independent variable. The 11-year average (2000-2010) CRE_{atm} (all-sky minus clear-sky) is overall positive at around +11 Wm^{-2} using direct measurements form ground and space, and at 4 Wm^{-2} in the CERES EBAF dataset. This discrepancy arises from a potential overestimation in clear-sky absorption by the satellite product or underestimation by the combined BSRN/CERES dataset. The forcing ratio R shows that clouds enhance ASR_{atm} most distinctly at desert-like locations that overall experience little occurrence of clouds. This relationship is captured by both the combined dataset and CERES EBAF.

INTRODUCTION

The absorption of solar radiation in the atmosphere (ASR_{atm}) and its representation by global climate models (GCM) has been studied for decades[1,2,3,4,5]. More recently, GCM biases in shortwave absorption have attained attention in the context of the Earth's hemispheric energy budgets, the meridional heat transport, and the location of the ITCZ[6]. From the observational perspective, consensus about the precise magnitude of ASR_{atm} and associated cloud effects has still not been reached. New estimates of all-sky ASR_{atm} including uncertainty ranges over Europe[7] have been obtained through combining direct observations from ground and space. In the present paper, we adopt this method and combine BSRN measurements with MODIS-derived surface albedo and CERES EBAF TOA irradiances to estimate the ASR_{atm} under all-sky and clear-sky conditions and quantify the cloud radiative effect on atmospheric solar absorption (CRE_{atm}) in the climatological annual mean (2000-2010).

METHODS

We follow the approach by Hakuba et al.[7] to estimate ASR_{atm} as the residual of the net incoming solar radiation at the top-of-atmosphere (TOA_{net}) and the absorption of solar radiation at the surface (ASR_{surf}). TOA_{net} is taken from CERES EBAF at 1° horizontal resolution. To estimate ASR_{surf}, we combine the BSRN surface solar radiation (SSR) with satellite-derived surface albedo (MODIS). In combining point-scale with gridded datasets, we expect collocation errors on the order of 3% (2 Wm^{-2})[8]. Using the automated method by Long and Ackerman[9] we derive continuous estimates of clear-sky SSR to obtain the ASR_{atm} under cloud-free conditions and subsequently the CRE_{atm} (all-sky minus clear-sky ASR_{atm}), presented for each site in Figure 2. Another measure of the cloud effect on ASR_{atm} is the forcing ratio R, the ratio of the CRE at the surface (ASR_{surf}) to the CRE at TOA. If the surface forcing exceeds the forcing at TOA (R >1), the presence of clouds yields an increase in ASR_{atm} (Figure 3).

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DATA

The Baseline Surface Radiation Network (BSRN) hosted by the Alfred Wegener Institute (AWI) in Bremerhaven, Germany (http://www.bsrn.awi.de/) provides high-accuracy surface radiation measurements at high temporal resolution (minutes). In the present study, we make use of 36 records; their location together with the observed clear-sky index (ratio of all-sky to clear-sky SSR) is shown in Figure 1. We applied quality checks using the approach by Long and Shi[10] and computed monthly means following the recommended approach by Roesch et al.[11]. The top-of-atmosphere (TOA) irradiances originate from the energy balanced and filled (EBAF) CERES dataset[12] version 2.8. The surface albedo we derive from the MODIS MCD43C1 Climate Modeling Grid (CMG) BRDF/Albedo Model Parameters Product[13] with respect to the monthly mean sun angle at the BSRN locations. Whenever a 1° monthly average of MODIS-derived albedo is missing, we use CERES EBAF surface albedo instead.

RESULTS

In Figure 2, we present the cloud radiative effect on atmospheric solar absorption (CRE_{atm}, Wm^{-2}) derived from 36 BSRN records (circles) combined with satellite-derived TOA net irradiance (CERES EBAF) and surface albedo (MODIS). The red-white-blue colors indicate each site's clear-sky index, i.e. the ratio of the all-sky (measured) to the clear-sky surface solar radiation (CI). The colored "error" bars indicate the monthly range with minima and maxima either occurring in the summer or winter half year, i.e. between March and August (orange) or September to February (green). At some locations, both the maximum and minimum occur in the same half year, while the majority experience the largest CRE_{atm} in summer. On average, the CRE_{atm} amounts to 11 Wm^{-2}. While the cloudier sites (CI < 0.7, blue colors) tend to exceed this multi-year average, sites with CI larger than 0.9 are associated with CRE_{atm} below average (red colors). To account for this discrepancy in cloud frequency between sites, we compute the forcing ratio R that draws an opposite picture (not shown) with largest R (R> than sample average at 1.3) observed at sites with little occurrence in clouds (large CI). At these desert-like sites, Alice Springs (ASP), De Aar (DAA), Desert Rock (DRA), Solar Village (SOV), Tamanrasset (TAM), the rare occurrence of clouds and the associated increase in column humidity, appear to enhance ASR_{atm} more strongly than in temperate or humid climates. The relationship of R and CI is shown in Figure 3, using the combined BSRN data (left) and the CERES EBAF dataset (right). Both figures show a relationship of exponential nature, but the BSRN-based estimates show a

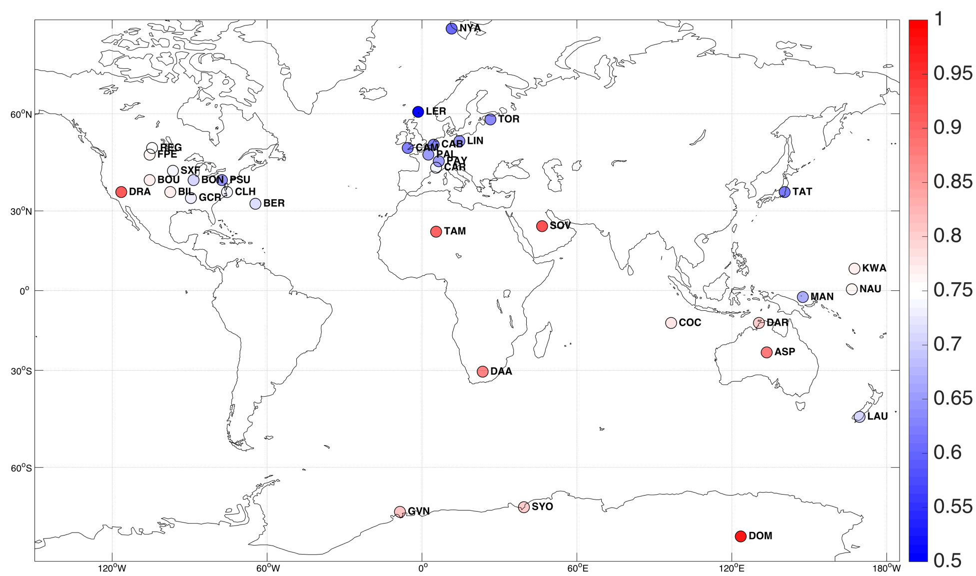

FIGURE 1 Locations of 36 BSRN sites used in this study. The colors (red-white-blue) indicate the clear-sky index, ratio of all-sky (measured) to clear-sky surface solar radiation. Red color refers to sites with relatively low cloud cover while blue refers to sites with more frequent cloud cover.

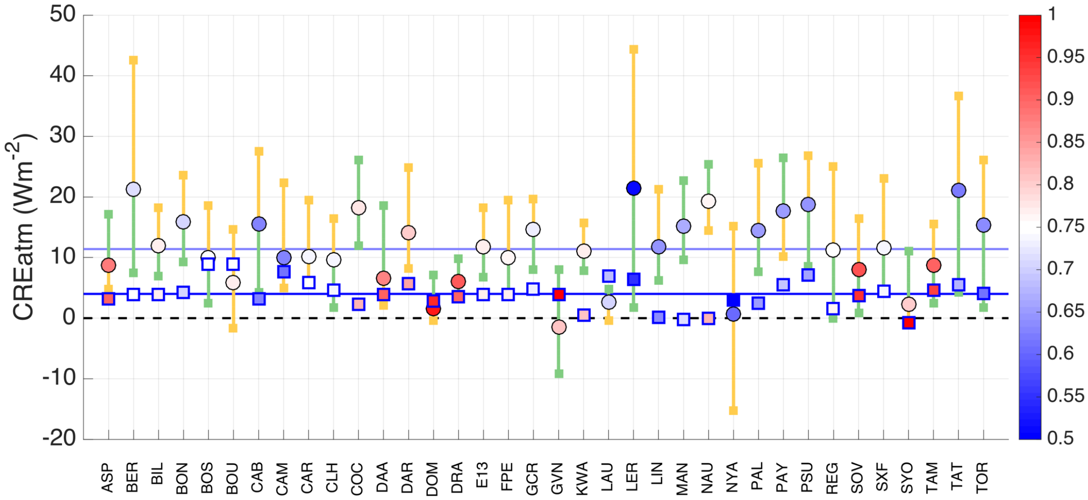

FIGURE 2 Atmospheric cloud radiative effect (CRE_{atm}) derived from 36 collocated BSRN and satellite observations (circles) as compared to CERES EBAF alone (squares). Colors (red-white-blue) indicate the corresponding clear-sky index. Error bars depict the monthly range of values with maximum/minimum either lying in the summer (yellow) or winter months (green). The BSRN-derived average (median) is at 11 Wm^{-2} (upper horizontal line), while CERES EBAF suggests 4 Wm^{-2} (lower horizontal line).

larger spread. This is to be expected as the CERES EBAF data are self-consistent and the BSRN/MODIS/CERES sample is a combination of different datasets with different uncertainties.

Notable is the systematic difference in CRE_{atm}. The CERES EBAF estimates (Figure 2, squares) are with 4 Wm^{-2} (averaged over same locations) significantly lower. The all-sky ASR_{atm} and SSR (bias: -2 Wm^{-2}) agree very well between the datasets[7], but the clear-sky SSR in CERES EBAF is lower by about 10 Wm^{-2}. This explains the smaller CRE_{atm} and larger clear-sky ASR_{atm} in the CERES EBAF. These differences are smaller at clear sites with larger CI when both retrievals, the Long & Ackerman[9] and the CERES radiative transfer code, should work at their best in deriving clear-sky SSR. Multiple reasons for this marked difference in clear-sky SSR and ASR_{atm} can be considered:

- The Long & Ackerman[9] algorithm derives clear-sky SSR based on the clearest, hence driest periods with little water vapor in the atmospheric column. This might lead to a "dry" bias with systematically larger clear-sky SSR or smaller ASR_{atm}, respectively. A similar bias can be expected in CERES EBAF, as the retrieval does not just remove the clouds, but is based on the clear-sky portions of a CERES footprint[12].
- The CERES retrieval may either overestimate the clear-sky ASR_{atm} or underestimate the net incoming clear-sky TOA radiation. Potential causes are the misclassification of cloudy scenes and lateral scattering from cloudy into non-cloudy regions. This may "artificially" enhance the reflection of solar radiation[12].
- If the clear-sky TOA net radiation (CERES EBAF) is too little, a combination with BSRN clear-sky SSR (potentially too much) would yield an underestimate in clear-sky ASR_{atm} and overestimate in CRE_{atm}. This said, the collocation approach may not be well-conditioned for the clear-sky case.

DISCUSSION AND CONCLUSIONS

Combining ground-based and satellite-derived solar radiation datasets under all-sky and clear-sky conditions, we estimate the cloud radiative effect on atmospheric solar absorption (CRE_{atm}) at 11 Wm^{-2} representative of 36 BSRN locations in different climate zones (2000-2010). The CRE_{atm} is significantly smaller when derived from the CERES EBAF TOA and surface products (4 Wm^{-2}). This discrepancy ensues from much lower clear-sky SSR in the satellite-based dataset as compared to the BSRN-derived estimates[9].

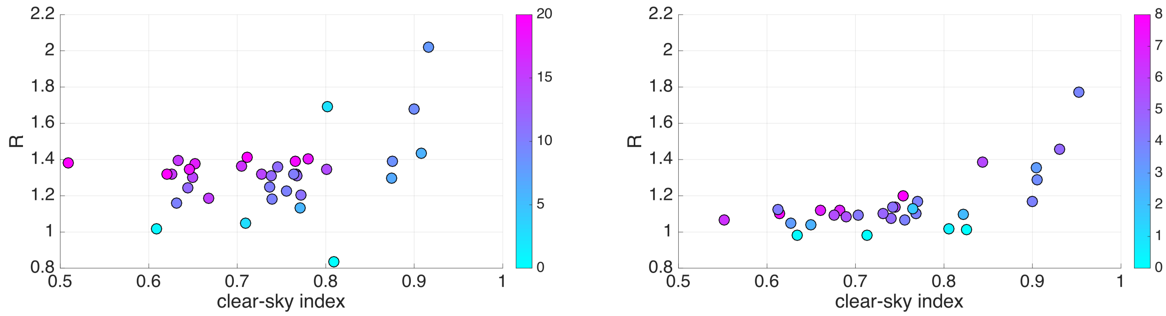

FIGURE 3 Forcing ratio R based on collocated BSRN and satellite observations (left) versus the clear-sky index. Colors indicate the corresponding CRE_{atm} in Wm^{-2}. Right: same as left, but based on CERES EBAF solely.

Both retrievals bear uncertainties and limitations. Nevertheless, they both exhibit a similar relationship between the forcing ratio R (measure for cloud effect) and clear-sky index. Hence, from a physical perspective, assuming that the presence of clouds enhances atmospheric absorption more strongly in dry environments than in temperate, the datasets agree. However, it has to be noted that R values larger than 1.2, as found with the combined BSRN/CERES dataset and especially at sites of less frequent cloud cover, are rather unlikely[14] and can result under conditions of heavy aerosol loading[15]. This effect we have yet to study.

Preliminary analysis of 40 CMIP5 historical simulations suggest a multi-model mean cloud effect at 3 Wm^{-2}, which is in reasonable agreement with the CERES EBAF. Nevertheless, the models underestimate the all-sky and clear-sky absorption by around 5 Wm^{-2} compared to the satellite product. On the near global scale, Hakuba et al. (2016)[3] studied the zonal variability of ASR_{atm} in CERES EBAF. They discuss the role of surface albedo, water vapor, and aerosols in shaping the slight hemispheric asymmetry in clear-sky ASR_{atm} and find that clouds and their different properties at different latitudes yield almost constant all-sky ASR_{atm} at around 23% of TOA incoming solar radiation.

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