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Satellite remote sensing methods for estimating clear Sky shortwave Top of atmosphere fluxes used for aerosol studies over the global oceans

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The difference between the top of atmosphere shortwave clear sky (cloud and aerosol free, SWCLR) and aerosol sky radiative fluxes is known as direct radiative effect (DRE) for all aerosols or Direct Climate Forcing (DCF) for anthropogenic aerosols. There are several methods for calculating SWCLR including satellite-based methods and radiative transfer approaches. Since uncertainties in SWCLR can propagate into errors in DRE or DCF, we assess the SWCLR estimates over the global oceans using three approaches and quantify the differences among these methods both as a function of space and season. Our results indicate that the more commonly used intercept (73.4 ± 3.6) and radiative transfer methods (74.7 ± 4.0 Wm^{-2}) are in close agreement to within ± 1.3 Wm^{-2}. Values of SWCLR are provided as a function of space and season that can be used by other studies that require such values or as a source of validation. We further recommend that research studies report the methods and assumptions used to estimate SWCLR to facilitate easier intercomparisons among methods.

1. Introduction

Tropospheric aerosols are usually defined as solid or liquid particles suspended in air that can be produced from both natural and anthropogenic sources. Examples of natural sources include sea salt aerosols over the global oceans and mineral dust from arid deserts while anthropogenic sources include smoke from agricultural burning and fossil fuel combustion. Although sub-groupings of anthropogenic aerosols do exist, they are in general characterized as sulfate (SU), black carbon (BC), and particulate organic matter (POM). Aerosol particles are usually categorized based on size including nucleation mode (0.001–0.1 μm diameter), accumulation mode (0.1–1 μm diameter), and coarse mode (>1 μm diameter). Much of the anthropogenic aerosols are found in the accumulation mode, whereas mechanically produced aerosols such as dust and sea salt are predominantly coarse mode aerosols. Considering that nearly 70% of the earth is ocean, it is not surprising that the total median sea salt aerosol source strength is the largest (6000 Tg $year^{-1}$) when compared to dust (1600 Tg $year^{-1}$) and BC, POM, and SU put together (300 Tg $year^{-1}$). However, in terms of median mass loading, dust has the highest mass (20 Tg) when compared to sea salt (6 Tg) with SU, BC, and POM totaling 4 Tg (CCSP 2009).

Aerosols have a wide range of impacts from affecting visibility to absorbing/scattering sunlight (direct radiative effect), acting as cloud condensation nuclei, and modifying cloud hydrological processes (indirect radiative effect). Although the lifetimes of tropospheric aerosols are less than a week, the ubiquitous nature of these sources and source strengths are important for various applications including climate and air quality. Moreover, their strong regional impacts are based on their absorptive and scattering properties, as well as the myriads of chemical compositions making the study of aerosols both challenging and interesting. A comprehensive review of aerosols and their climate effects from both an observational and a modeling perspective is presented in the CCSP report and by Yu et al., (2006 and references therein). Both DRE and DCF quantify the change in shortwave radiation (0.2-4.5 μm) with and without aerosols at the top of atmosphere (TOA) (usually at 20 km ASL). The TOA is especially useful since global measurements of reflected solar radiation are available from a routine basis from satellites over several decades (Anderson et al., 2005). In general, aerosols tend to reduce the amount of solar radiation reaching the surface thereby cooling the surface. In contrast, the effect of the absorption and emission of anthropogenic CO_2 is to warm the earth's surface. Therefore, the competing cooling of the aerosol effect compared to the warming CO_2 effect has been a topic of much debate (Andreae et al., 2005).

The definition of CO_2 forcing is well established in the literature and represents the change in TOA radiative fluxes from current day CO_2 conditions to pre-industrial values. However, complications arise when discussing aerosol forcing since definitions among methods vary (Bellouin et al., 2008). Modeling studies define aerosol forcing (due to anthropogenic aerosols only) as the change in radiative fluxes at the TOA from current day aerosol concentrations to pre-industrial values.

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Since it is difficult to pin down pre-industrial aerosol concentrations spatially and seasonally, satellite-based studies define aerosol effects as the change in radiative fluxes between current day aerosol conditions and conditions when aerosols are not present. Bellouin et al. (2008) examines this definition-problem and discuss the utility of using current day natural aerosol distribution as pre-industrial aerosols. They note the complexity of this issue since most satellite-based studies are only adept at assessing aerosols in cloud-free conditions and open questions such as accuracy of emission sources and processes in numerical simulations remain. Assessing aerosol impacts in the presence of clouds is still an unsolved issue, since neither satellite-based studies nor modeling simulations adequately characterize the relative positions of aerosols and clouds and their associated radiative properties. While differences between modeling and satellite-based studies have been reduced, they have yet to be fully and completely reconciled due to varying definitions of aerosol types (Bellouin et al., 2008) and aerosol absorption (Myhre et al., 2009).

Many uncertainties exist when calculating DRE using observational methods and include sensor calibration, sampling resolution, cloud clearing quality, accuracy of radiance to flux conversions, among many others (Christopher et al., 2006) which are not the focus of the paper. They are addressed in Yu et al., (2006). Another important uncertainty that requires further analysis is that pertaining to the cloud and aerosol free backgrounds (that we label clear sky flux) used to calculate DRE. Recall that DRE is defined as the difference between clear and aerosol sky fluxes. Thus, any uncertainty in clear sky fluxes will propagate through to the final DRE calculations although compensating effects are possible. To address this issue, we take a closer look at the shortwave clear sky fluxes (SWCLR) that are used to compute aerosol forcing in satellite-based studies. Satellite-based studies define DRE or DCF as SWCLR-SWAER where SWCLR is clear sky (no clouds or aerosols) TOA flux and SWAER is aerosol sky flux. Note that the effects of aerosols on thermal radiation are not considered in this paper and depending upon particle size and absorption characteristics, their effects could be significant.

Several methods have been used to create SWCLR from CERES-based observations. The first uses a regression technique whereby top of atmosphere clear sky fluxes are assumed to have a linear correlation to AOD (while also being a function of atmospheric conditions, satellite viewing geometry, and surface conditions). The intercept to the regression equation where AOD = 0 is then defined as SWCLR. In some cases, the regression method is not applied and the minimum flux value within a region of cloud-free data is assumed to be the clear sky flux (Christopher & Zhang, 2002). However, this method breaks down in regions where cloud and/or aerosol cover are consistently high. Another method often used by the research community is the radiative transfer (RT) model method. Using this technique, clear sky fluxes are calculated from radiative transfer models using atmospheric conditions, surface albedo, and viewing geometry inputs for a pristine, clear sky conditions. At least one study (Kato et al., 2002) has examined the differences in between these methods (regression and RT) using CERES and VIRS data from the TRMM satellite. For the region bounded by ±40° latitude, they found a total uncertainty of 1.2 Wm^{-2} between these methods with the RT method producing albedos 3% to 4% higher than the regression method, resulting in higher clear sky SW fluxes.

However, the combination of MODIS and CERES on Terra and Aqua is better suited to assess cloud free fluxes. The VIRS had limited spectral channels and the TRMM only provided data between ~40°N-40°S. Better angular models for surface and aerosols (Zhang et al., 2005) have been developed as well. Furthermore, the AOD retrievals from MODIS are considered a much newer generation of retrievals compared to the two channels methods employed for the VIRS. We examine three methods of obtaining SWCLR over the global oceans and quantify these values as a function of season and region to determine which methods are best suited for studies of DRE and/or DCF, while noting the advantages and disadvantages of each.

2. Methods

We use the CERES Single Satellite Footprint (CERES-SSF, FM3, Edition 2C) product from the Aqua satellite between May 2006 and August 2007 (Wielicki et al., 1996). This CERES contains point spread function weighted MODIS collection 5 aerosol optical depth within each CERES footprint. The nadir spatial resolution is 20 km for CERES and the MODIS aerosol product is 10 km at nadir. For aerosols, the CERES converts the TOA measured radiances to fluxes based on theoretical radiative transfer calculations and TRMM data (Loeb et al., 2005). To improve upon this approach, the CERES total upward shortwave radiance between 0.2 and 4.5 µm (SDS-35) are converted to SW fluxes using angular dependence models that were specifically derived for aerosols from Terra (Zhang et al., 2005). This product has been used extensively for studying aerosol forcing (e.g. Christopher et al., 2006) over the global oceans and therefore used in this study. Note that the anthropogenic fraction of the total AOD must be first obtained before calculating DCF estimates. (e.g. Kaufman et al., 2005). Over the global oceans, *the cloud-fre*e DCF is about 4 times smaller (−1.4 Wm^{-2}) than the total DRE (−5.5 Wm^{-2}) (Christopher et al., 2006). However, we are primarily concerned with the total aerosol DRE in this research and the additional uncertainties associated with separating the anthropogenic component of AOD are discussed in other literature (e.g. Christopher et al., 2006).

The CERES Fixed Swath Width (FSW) data product (Aqua, FM3, Edition 2C) at 1 × 1° degree resolution contains the monthly gridded FSW product that were from hourly single satellite swath fluxes. We use the upward SW flux for pristine conditions (no-clouds and no-aerosols) parameter (SDS-46) in the FSW product that was calculated from the instantaneous Clouds and Radiative Swath (CRS) using a 4-stream radiative transfer model (Fu & Liou, 1993; Rutan et al., 2006). The 4-stream model uses atmospheric profiles (temperature and water vapor) from Goddard Earth Observing System Data Assimilation System, version 4 GEOS-4, ozone profiles from National Center for Environmental prediction (NCEP), and spectral surface albedo based on wind speed, cholorophyll concentrations, and sea foam to estimate TOA flux for those conditions in the wavelength band between 0.2 and 4.5 µm. After the first model pass, TOA results are compared with CERES TOA fluxes (that use empirical ADM's from above) and the model is adjusted by changing surface and atmospheric conditions to produce a better match. The resulting instantaneous SWCLR values have an estimated error of ± 5 Wm^{-2}. It should be noted that while the model-based SW flux values are derived directly from the RT model, the final values are adjusted to fit actual observations that do use the ADM. Thus, this step does improve the overall agreement between the two products. We make use of the FSW-based SWCLR estimates over the same spatial and temporal domains as our observational based SWCLR estimates to examine the differences between aerosol-free fluxes obtained from these two methods. While there are several approaches for simulating the clear sky values over the global oceans, we use the FSW product merely as an example.

Our goal is to obtain the seasonal and spatial distribution of SWCLR both spatially and seasonally from the methods mentioned above. Fig. 1 shows the framework for the problem. In this figure, SWCLR below the aerosol layer labeled SWCLR-A is the desired value. However, when aerosols are present above the ocean surface, CERES can only obtain reflected solar radiation information from the aerosol layer. Therefore, approximations are necessary to obtain SWCLR. Perhaps the most commonly used method to obtain is to examine the relationship between AOD and the shortwave flux for all cloud-free pixels. Then the regression line is extrapolated back to zero AOD and the ordinate value is approximated as SWCLR (Christopher et al.,