CURRENT PROBLEMS IN ATMOSPHERIC RADIATION (IRS 2008)

Proceedings of the
International Radiation Symposium (IRC/IAMAS)

Foz do Iguaçu, Brazil   3 – 8 August 2008

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AMERICAN INSTITUTE OF PHYSICS

Melville, New York, 2009
AIP CONFERENCE PROCEEDINGS ∎ 1100

The Shortwave Radiative Forcing Bias of Homogeneous Liquid and Ice Clouds Observed by MODIS

Lazaros Oreopoulos[a,b], Steven E. Platnick[b], Gang Hong[c], Ping Yang[c], and Robert F. Cahalan[b]

[a]*JCET, University of Maryland Baltimore County, Baltimore, MD, USA*
[b]*Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, MD, USA*
[c]*Department of Atmospheric Sciences, Texas A&M University, College Station, TX, USA*

Abstract. We analyze the plane-parallel bias of the shortwave cloud radiative forcing (SWCRF) of liquid and ice clouds at 1 degree scales using global MODIS (Terra and Aqua) cloud optical property retrievals for four months of 2005 representative of the meteorological seasons. The (negative) bias is estimated as the difference of the SWCRF calculated using the Plane-Parallel Homogeneous (PPH) method and the Independent Column Approximation (ICA). These calculations require MODIS-derived means (for PPH calculations) and distributions (for ICA calculations) of cloud optical thickness and effective radius as well as ancillary surface albedo and atmospheric information, that are inserted into a broadband solar radiative transfer code. The absolute value of global SWCRF bias of liquid clouds at the top of the atmosphere is ~6 Wm^{-2} for MODIS overpass times while the SWCRF bias for ice clouds is smaller in absolute terms by ~0.7 Wm^{-2}, but with stronger spatial variability. Marine clouds of both phases are characterized by larger (more negative) SWCRF biases than continental clouds. For clouds of both phases the SWCRF bias is collectively about 4 Wm^{-2} for diurnal averages.

Keywords: clouds, cloud radiative forcing, inhomogeneity, MODIS.
PACS: 92.60.Vb

INTRODUCTION

In a recent study [1] examined the albedo bias when the variability of Moderate Resolution Imaging Spectroradiometer (MODIS) optical thickness and effective radius within 1° regions covered by liquid clouds is neglected and mean values are used instead. This so called Plane-Parallel Homogeneous (PPH) bias assumed values of 0.03, i.e., about 10% of the liquid cloud albedo calculated with spatial cloud variations included. The motivation behind that study was the lack of extensive global mapping of the PPH bias, considering that previous published satellite studies were mainly assessments of the visible PPH bias over limited parts of the globe [2, 3, 4] or did not report on the climatology of broadband bias, but rather on parameters quantifying the underlying cloud horizontal inhomogeneity [5, 6]. This work expands upon [1] by providing better seasonal coverage and by including also clouds classified by MODIS to be of ice phase (near cloud top). A newer, improved version of MODIS cloud data is used, and emphasis in now placed on the shortwave (SW) Cloud Radiative Forcing (SWCRF) bias which not only conveys directly the energy budget impact of the bias, but also takes into account the areal coverage and frequency of occurrence of the two (liquid and ice) cloud types. The SWCRF bias analysis is given a more thorough treatment in a recently submitted paper [7] and along with the online collection of PPH albedo biases from the International Satellite Cloud Climatology Project (ISCCP) provides a fairly comprehensive picture on the radiative effects of neglecting horizontal cloud inhomogeneity. Any global models that aspire to produce clouds with subgrid variability as well as super-parameterization approaches should find these datasets valuable for validation purposes.

CP1100, *Current Problems in Atmospheric Radiation (IRS 2008)*
edited by T. Nakajima and M. A. Yamasoe

DATASET AND RADIATIVE TRANSFER CALCULATIONS

We use daily MODIS Level-3 Collection 5 (gridded 1°x1°) daytime data from both the Terra (~10:30 local time overpass) and Aqua (~13:30 overpass) satellites (datasets MOD08_D3 and MYD08_D3, respectively) for January, April, July, and October 2005. We extract the mean daily values of vertically integrated optical thickness (τ), effective radius (r_e), cloud fraction of successful cloud retrievals (A_c), and solar zenith angle (SZA), as well as joint (2D) histograms of τ-r_e and τ-cloud top temperature (T_c). Except for high latitudes where gridboxes can be revisited within the same day due to orbital swath overlap, the daily histograms represent the instantaneous spatial variability of τ and r_e within 1°x1° gridboxes.

The radiative transfer calculations yielding daily atmospheric column albedo are performed with a version of the broadband SW Column Radiation Model (CORAM) of [8]. The salient features of this code and the manner in which it is interfaced with the MODIS retrievals, atmospheric information and MODIS-derived surface albedo is described in [1] and [9]. In these radiative transfer calculations the cloud is placed in the layer whose top temperature is closest to the mean cloud top temperature as derived from the joint histogram of τ and T_c. Since the MODIS-inferred cloud properties are placed in a single layer there is no cloud overlap to deal with.

An important modification in our version of the CORAM is the introduction of a new method of calculating cloud optical properties (extinction, single-scattering albedo, asymmetry factor). The changes implemented for liquid clouds are described in [1] and [9]. For ice clouds a new parameterization of scattering properties is used based on the ice particle single-scattering properties of [10]. The ice habit distribution is consistent with that used for the MODIS retrieval look-up tables of Collection 5, which come from [11]. The visible MODIS optical thicknesses were appropriately scaled for use in the CORAM bands with wavelengths above the visible.

[1] showed that the albedo bias B^R (difference between the inhomogeneous independent column approximation ICA albedo from the joint τ-r_e histogram and the plane-parallel homogeneous PPH albedo using the mean τ, r_e values) and the bias in the top-of-the-atmosphere shortwave cloud radiative forcing $\Delta SWCRF$ are simply related via:

$$\Delta SWCRF(<0) \equiv SWCRF_{PPH} - SWCRF_{ICA} = -A_c B^R \mu_0 S_0 \tag{1}$$

where the *SWCRF* is simply defined as the difference in reflected solar fluxes between cloudless and all-sky (i.e., including clear-cloud mixtures) conditions, μ_0 is the cosine of the solar zenith angle, and S_0 is the incident solar irradiance at TOA. Note that since $B^R > 0$, $\Delta SWCRF$ is a negative quantity which does not require separate estimation of the individual PPH and ICA *SWCRF*s because the cloudless sky fluxes are identical and cancel out. The negative sign of the *SWCRF* bias is dropped hereafter for simplicity. The *SWCRF* bias estimates are performed for each day of the month in each illuminated gridbox with valid MODIS cloud property retrievals, and are then arithmetically averaged to monthly values. Zonal and global averages of the gridpoint monthly values are trivially estimated as in [1], but with non-illuminated gridpoints contributing zero to the averages.

SWCRF BIAS FROM MODIS

The mean Terra-Aqua global biases for three types of $\Delta SWCRF$, "overpass" (using the mean SZAs of the MODIS dataset), "day", and "24h" (taking into account solar illumination variations during daytime and over 24 hours as in [1] and [7]) are shown in stack-bar graph form in Fig. 1. The values in parentheses indicate the ratio of global mean to standard deviation for the overpass case. $\Delta SWCRF$ for ice clouds is more spatially variable than for liquid clouds and there is a slight tendency of greater dispersion for the vernal and autumnal months compared to the winter and summer months. Due to the seasonal changes in the geographical distribution of the SWCRF bias, the latitudinal dependence of daytime length, and the collective non-linearity of the global calculation, an empirical conversion of global overpass bias to global daytime or diurnal bias is not possible: the ratio of daytime to overpass global bias ranges from ~0.65 to 0.78, while the ratio of diurnal to overpass global bias spans an approximate 0.32 to 0.42 range. Overall, liquid clouds exhibit larger ΔSWCRF than ice clouds (~6.1 vs. 5.4 Wm^{-2} for overpass bias), with the largest disparity taking place in January (>1 Wm^{-2} for overpass bias) and the smallest in April (< 0.25 Wm^{-2} for overpass bias, increasing interestingly to about 0.5 Wm^{-2} for daytime bias). The relative seasonal variability of bias is stronger for liquid clouds, especially for daytime or diurnal averages.

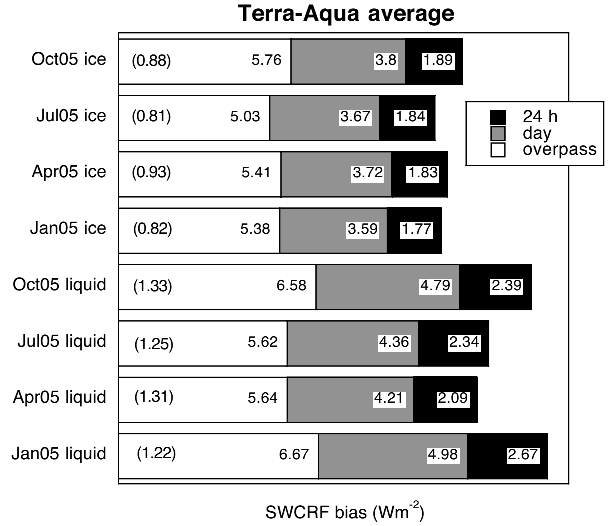

FIGURE 1. Stack-bar plot showing the combined MODIS Terra-Aqua global monthly-averaged SWCRF bias for liquid and ice clouds for the four months used in this study. Overpass, daytime, and diurnal (24-hour) values are shown (see [1] and [7] for definitions). The values in parentheses are the ratios of of global mean to standard deviation for the overpass case.

The zonal distribution of monthly $\Delta SWCRF$ (Terra-Aqua averages) is shown only for January and July. In this case we chose to show the 24-h biases to capture latitudinal changes in sunlight duration. Features that are prominent are the summer peaks in mid-latitude liquid $SWCRF$ bias which assume values close to 7 Wm^{-2} and come mainly from oceanic regions. The ice $\Delta SWCRF$ peaks are somewhat smaller and appear in the equatorial zone, shifting with the seasonal movement of the ITCZ. Even though plentiful solar illumination is available, minima occur in broad subtropical zones where deserts and homogeneous marine stratocumulus regions are prevalent (the bias of these clouds peaks in October when cloud fraction is maximum).

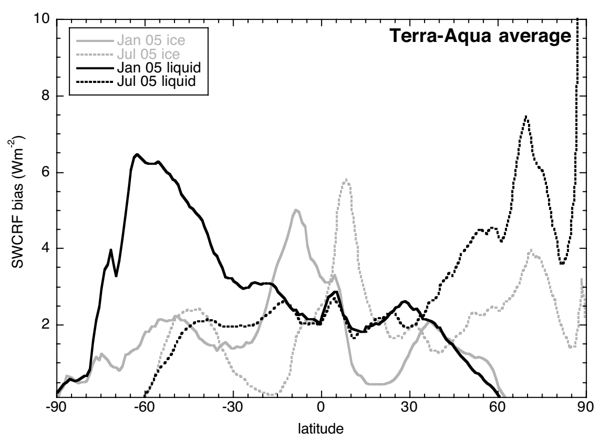

FIGURE 2. Zonal dependence of the combined Terra-Aqua monthly 24-h SWCRF bias for January and July 2005.

Land-ocean global overpass $\Delta SWCRF$ differences are highlighted in Figure 3. The bias is clearly greater over oceans for both cloud types and all months with the exception of July where liquid biases are very similar over land and ocean. This was traced to the dramatic decrease of $\Delta SWCRF$ over the southern midlatitude oceans due to the lower winter solar illumination. Besides differences in cloud hetereogeneity, cloud fraction, and availability of solar insolation, the overall lower land $SWCRF$ bias is probably also partly attributable to the brighter land surfaces which tend to reduce the cloud albedo contribution to the TOA albedo and therefore dampen albedo differences between homogeneous and inhomogeneous clouds.

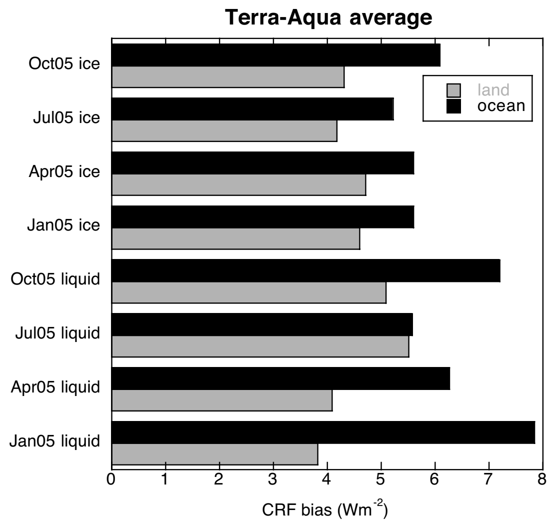

FIGURE 3. Monthly combined Terra-Aqua overpass SWCRF bias averaged separately over the globe's land and ocean gridpoints.

CONCLUSIONS

If one wants to distill this analysis to a single representative number of the lower limit of global SWCRF bias, then the diurnal "24 h" values of Figure 1 provide guidance. Taking the arithmetic mean of the four monthly values yields a SWCRF bias is 2.37 Wm^{-2} for liquid clouds and 1.83 Wm^{-2} for ice clouds. Due to the nature of MODIS observations where liquid and ice clouds cover different portions of the gridpoint, these numbers can be added for a total of 4.2 Wm^{-2} as an estimate of the lower bound of global SWCRF bias for 1 degree areas. The "lower bound" designation is justified by the omission of the relatively small fraction of MODIS "mixed" and "undetermined" clouds and the inclusion of zero contributions from cloudless and non-illuminated areas. Still, a more accurate assessment would require knowledge of the full diurnal variation of cloud properties, and more sophisticated treatments of atmospheric and surface albedo effects. Our SWCRF biases should provide a valuable validation reference for global modeling approaches that are able to generate mesoscale cloud inhomogeneity (at ~ 1 deg), provided that some the models extend some effort to simulate the MODIS worldview.

ACKNOWLEDGMENTS

L. Oreopoulos gratefully acknowledges support from the U.S. DOE, Office of Science, Office of BER, Environmental Sciences Division as part of the ARM program under grant DE-FG02-07ER64354.

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