Estimate of Solar Radiative Forcing by Polluted Clouds Using OMI and SCIAMACHY Satellite Data

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Abstract. Absorbing aerosols, like smoke, can potentially have a large heating effect if they are situated above bright clouds. However, the detection of aerosols in the presence of clouds is not possible for satellite imagers operating in the visible. We use the Absorbing Aerosol Index (AAI) from OMI and SCIAMACHY ultraviolet radiances to detect aerosols in cloudy scenes. We first determine the global occurrence of events in 2006 with high effective cloud fraction (> 0.5) and appreciable amount of absorbing aerosols (AAI > 1) from OMI and SCIAMACHY data. These events we call polluted clouds. Next we zoom in on SW-Africa, where polluted clouds occur most frequently, especially in the months JJAS. Using SCIAMACHY reflectance measurements, polluted clouds appear to have a shortwave spectral reflectance that is lower than that of clean clouds from the UV until about 1050 nm. We determine the difference in reflectance between clean clouds and polluted clouds, and integrate the spectral difference from 280 to 1050 nm to obtain the solar radiative forcing of polluted clouds as compared to clean clouds. We find that in case of polluted cloud events in SW-Africa, a shortwave heating of the atmosphere in the range of 0-80 W/m^2 occurs, with a mean of 35 W/m^2.

Keywords: Shortwave absorption, absorbing aerosols, clouds, AAI, OMI, SCIAMACHY
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INTRODUCTION AND OVERVIEW

The impact of aerosols on the Earth's albedo and radiation balance, through their direct radiative effects and their indirect effects on the formation and modification of clouds, is an active area of climate research. An important aspect in this area is the lowering of the cloud albedo due to absorbing aerosols inside and/or above the cloud. However, it is difficult to obtain quantitative information from satellites on this direct radiative effect. The reason is that most aerosol detection algorithms fail in the presence of clouds, because cloudy scenes are considered to be too bright to allow aerosol retrieval. This detection problem can be avoided by the use of the absorbing aerosol index (AAI) to detect absorbing aerosols. The AAI is a differential spectral index to identify UV absorbing aerosols, like desert dust and smoke. The strength of the AAI aerosol detection method is that it works equally well for land and sea surfaces, and that it works even in the presence of clouds [1].

Observations from the Ozone Monitoring Instrument (OMI) on EOS/Aura are used to combine AAI and cloud information for 6 months of global data in 2006. OMI, launched in 2004, observes the whole Earth in one day with a pixel size of 13x24 km^2 at nadir and covers the spectral range 270-500 nm. We identify scenes where absorbing aerosols occur in the presence of clouds; these scenes we call polluted clouds. Polluted clouds are mostly due to biomass burning (wildfires) in the tropics and at high northern latitudes.

The global information on polluted clouds from OMI is being combined with the extensive spectral information from another satellite instrument, SCIAMACHY on Envisat, launched in 2002. SCIAMACHY measures the Earth's reflectance from 240 to 1750 nm (bands 1a-6) contiguously with a pixel size of 30x60 km^2 for most wavelengths and achieves global coverage in 6 days. This range of 280-1750 nm contains 92 % of the solar energy. Therefore, SCIAMACHY can be used to determine the largest part of the top-of-atmosphere solar radiative forcing of aerosols and clouds. It appears that clouds that exist in the presence of biomass burning aerosols have a typical reflectance spectrum, with a lower reflectance in the UV and visible than clean, unpolluted clouds. This lower reflectance is

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caused by the absorption of aerosols above and inside the clouds. Since the optical thickness of aerosols decreases with wavelength, the absorption is strongest at the shorter wavelengths [2]. From integration of the measured reflectance spectrum of polluted clouds over the SCIAMACHY wavelength range, we obtain an estimate of the shortwave absorption of polluted clouds as compared to clean clouds. Since this heating effect of absorbing aerosols is often neglected, this estimate contributes to the determination of the total direct radiative effect of aerosols.

OCCURRENCE OF POLLUTED CLOUDS

Using the following criterion for each satellite pixel:

$$AAI > 1 \quad \underline{and} \quad effective\ cloud\ fraction > 0.5,$$

we obtain the occurrence of the polluted cloud events from OMI and SCIAMACHY data in 2006, shown in Fig. 1a-b. We see that most polluted clouds occur in SW-Africa. In this area smoke from biomass burning drifts over the low clouds that frequently occur over the ocean west of Angola and Namibia [2]. There are also land regions in SW-Africa with frequent polluted cloud events, e.g. Gabon. Note that the frequency of occurrence is much larger in OMI data than in SCIAMACHY because OMI has 6 times more overpasses and a higher spatial resolution. The grid used for OMI data (Fig. 1a) is 0.5° x 0.5°, whereas the grid for SCIAMACHY data (Fig. 1b) is 1° x 1.25° (lat x lon). From these figures we find that the maximum frequency of occurrence of polluted cloud events in SW-Africa is about 15 % in the months JJAS.

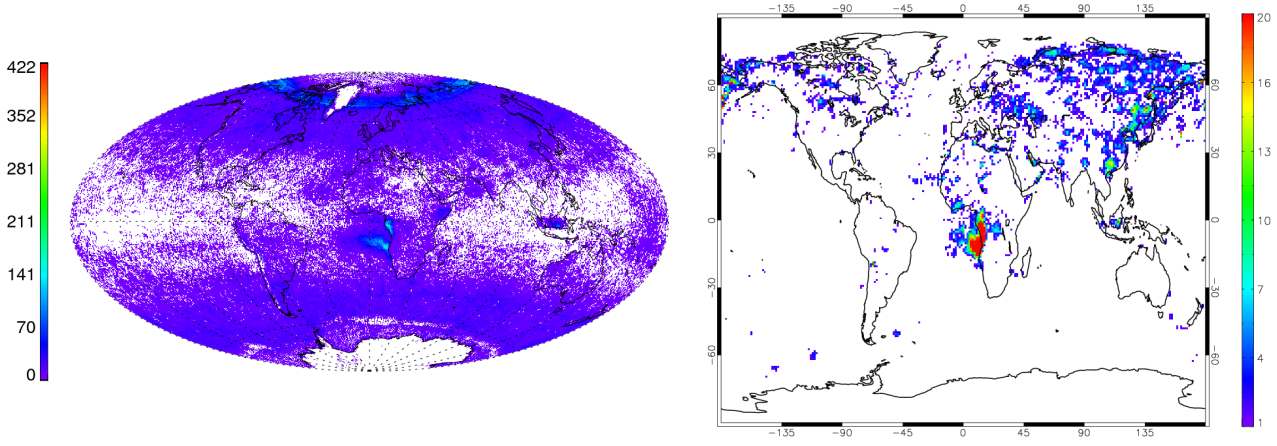

FIGURE 1. (a, left) Frequency of occurrence of polluted clouds in the period May-November 2006 from OMI data on a 0.5° x 0.5° grid. **(b, right)** Same as (a) but for the period January-December 2006 from SCIAMACHY data on a 1° x 1.25° grid. Note the different color scales.

REFLECTANCE SPECTRA OF POLLUTED CLOUDS

Since most polluted clouds occur in the region of SW-Africa, we consider a 30° x 30° area, 10° N – 20° S, 10° W – 20° E which covers the events' locations. This area includes ocean and land. Typical spectra of polluted cloud and clean cloud scenes over ocean as measured by SCIAMACHY are shown in Fig. 2a. The clean cloud is defined as having an effective cloud fraction > 0.5 but AAI < 0. We clearly see that the polluted cloud has a much lower reflectance at short wavelengths than the clean cloud, but is converging toward the clean cloud spectrum at longer wavelengths, beyond about 1000 nm. The best way of explaining this spectrum is by assuming that the smoke layer resides above the cloud layer [2]. Smoke has a gray absorption spectrum in the visible. But since smoke aerosols are small particles, with an aerosol optical thickness (AOT) which depends as about $\lambda^{-1.5}$, the smoke layer has the largest optical thickness at the shortest wavelengths. Due to multiple scattering between the cloud and the smoke layer, the smoke layer is most efficiently absorbing at short wavelengths, and this decreases the reflectance of the polluted

cloud [2]. At longer wavelengths the AOT of the smoke layer is small, and not much effect is noticed in the reflectance.

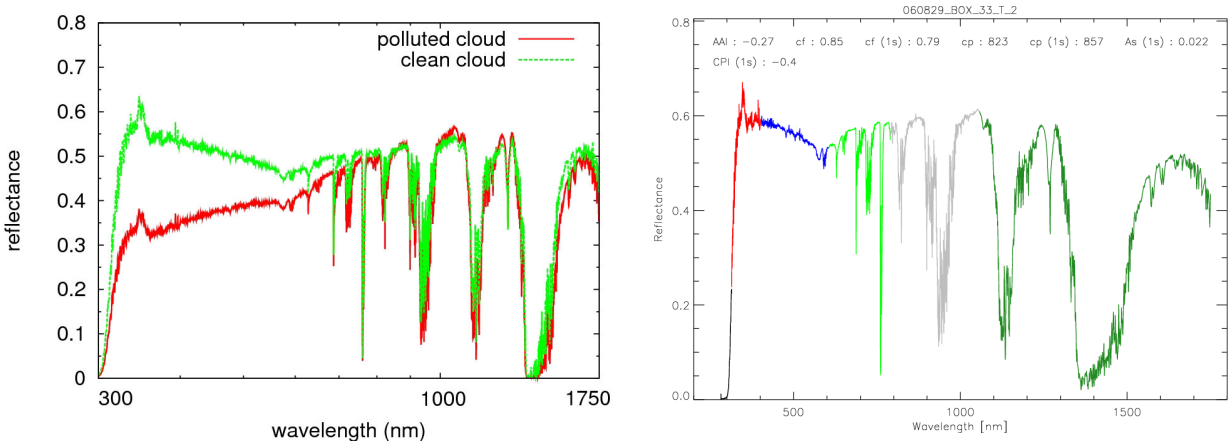

FIGURE 2. (a, left) Typical reflectance spectra of polluted cloud and clean cloud scenes in SW-Africa, measured by SCIAMACHY, L1 version 6.03. **(b, right)** Reference clean cloud spectrum, from 29 Aug 2006, box 33 (ocean). The feature around 350 nm is due to a radiometric calibration error in the SCIAMACHY L1 data.

To represent the SCIAMACHY reflectance spectra of all polluted cloud events in the 30° x 30° area in an efficient way, the area was divided into 36 5° x 5° boxes. For each box, three polluted cloud spectra were stored for each day of 2006, namely the spectra with minimum AAI, mean AAI, and maximum AAI. Not always three spectra were available; then none, or only minimum, or minimum and maximum spectra were stored. Since most events occurred in August, spectra of clean clouds were stored for August 2006 using the same procedure, but with the criterion of AAI < 0 instead of AAI>1.

RADIATIVE FORCING ESTIMATE FOR SW-AFRICA

To obtain the radiative forcing of the smoke layer in polluted cloud events, we need to determine the difference in reflectance spectrum between a polluted cloud and a clean cloud with both having the same cloud properties. Thereto we assume that the smoke layer has a negligible effect at 1050 nm. We used a reference clean cloud spectrum taken from the SCIAMACHY spectra of August 2006 (see Fig. 2b). From radiative transfer calculations using the DAK model [3] we found that the spectra of clean clouds with optical thickness larger than about 10 can be scaled quite well with a single multiplicative factor. For each polluted cloud spectrum we determined this scale factor from the ratio of the polluted cloud reflectance at 1050 nm to that of the reference clean cloud reflectance at 1050 nm.

The absorbed solar irradiance of a polluted cloud event, ΔE, is now found by multiplying the spectral reflectance difference between a polluted cloud spectrum and the scaled clean cloud reference spectrum, $\Delta R(\lambda)$, by the extraterrestrial solar irradiance spectrum $E_0(\lambda)$ [4] , and spectrally integrating the product between 280 and 1050 nm. The solar zenith angle and day of the year of each measurement are taken into account. Here it is assumed that the reflectance difference is the same as the albedo difference, i.e. that thick clouds can be approximated as isotropic reflectors.

The results for the absorbed solar irradiance ΔE of polluted clouds in SW-Africa are shown in Fig. 3. The absorbed irradiance lies in the range of 0 - 80 W/m^2. The absorbed irradiance versus the day number in 2006 (Fig. 3a) shows that most events occur in the months JJAS. The absorbed irradiance versus the AAI (Fig. 3b) shows that ΔE increases with AAI. Furthermore, Fig. 3 shows that polluted cloud events over land have higher absorbed irradiance than over ocean: the average ΔE is 27 ± 14 (1σ) W/m^2 for ocean scenes, and 47 ± 18 (1σ) W/m^2 for land scenes. The reason could be that the reference clean cloud spectrum is an ocean spectrum and not fully representative for land scenes which have a high surface reflectance in the near-IR. In order to investigate this land/ocean difference, we

calculated ΔE for clean clouds, defined as scenes having an effective cloud fraction > 0.5 but AAI < 0. For clean clouds ΔE should be 0, but we find -7 ± 13 (1σ) W/m^2 for ocean scenes and 10 ± 30 (1σ) W/m^2 for land scenes, in August 2006. We consider these values as a bias in the ΔE of polluted clouds. Subtracting this bias, we obtain a corrected ΔE value of polluted clouds, namely 34 ± 14 (1σ) W/m^2 for ocean scenes and 37 ± 18 (1σ) W/m^2 for land scenes. These values are very comparable, so we conclude that the absorbed irradiance of polluted clouds over ocean and land in SW-Africa is on average 35 W/m^2 with a standard deviation of 14-18 W/m^2.

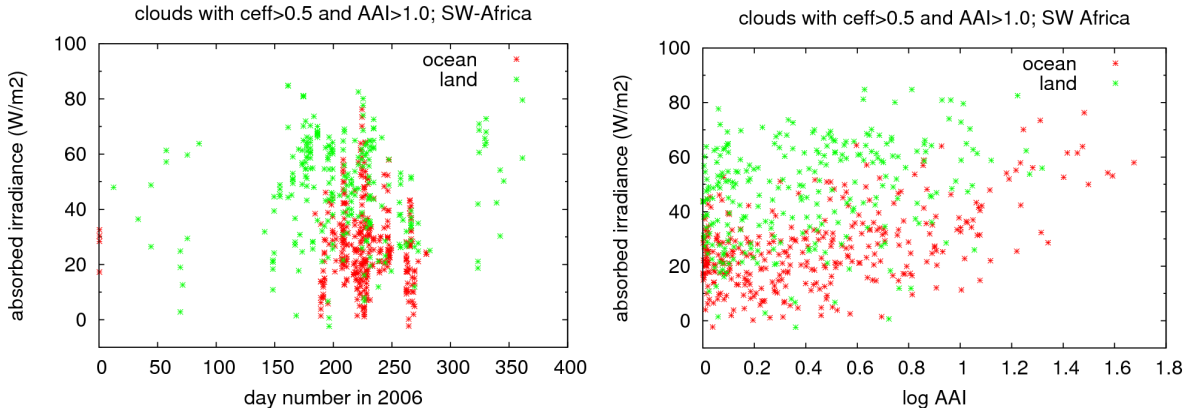

FIGURE 3. (a, left) Absorbed solar irradiance of polluted clouds in SW-Africa in 2006 calculated from SCIAMACHY reflectance spectra. This absorbed irradiance is the extra heating - as compared to clean clouds - due to the absorbing smoke layer. **(b, right)**. Absorbed irradiance versus the natural logarithm of the AAI. Note that most polluted cloud events have AAI between 1 and 3.

CONCLUSIONS

We studied the occurrence of polluted cloud events in 2006 from OMI and SCIAMACHY satellite data. These events have an AAI above 1 and an effective cloud fraction above 0.5. We find from global data that most events occur in SW-Africa. In that region the months JJAS have most frequently events with smoke above clouds, with a peak frequency of 15 % of the time. From the difference in reflectance spectra between polluted and clean clouds as measured by SCIAMACHY between 280 and 1050 nm, we find that the (instantaneous) absorbed solar irradiance in the smoke layer above clouds in SW-Africa is about 35 W/m^2, with a standard deviation of 14-18 (1σ) W/m^2. This absorbed solar irradiance is a heating effect by smoke aerosols, and forms an important part of the direct radiative effect of aerosols.

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