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Southeast Atlantic Ocean Aerosol Direct Radiative Effects Over Clouds: Comparison Of Observations And Simulations

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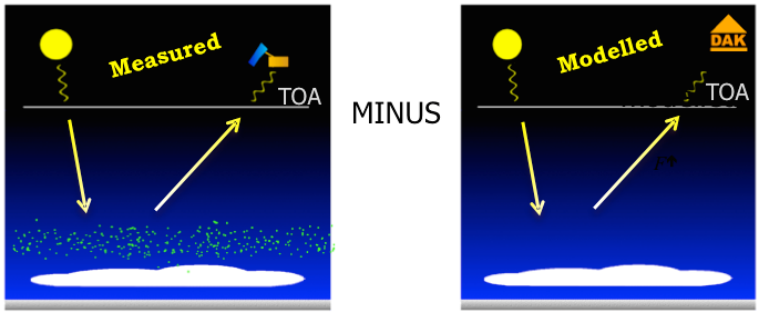
Abstract. Absorbing aerosols exert a warming or a cooling effect on the Earth's system, depending on the circumstances. The direct radiative effect (DRE) of absorbing aerosols is negative (cooling) at the top-of-the-atmosphere (TOA) over a dark surface like the ocean, as the aerosols increase the planetary albedo, but it is positive (warming) over bright backgrounds like clouds. Furthermore, radiation absorption by aerosols heat the atmosphere locally, and, through rapid adjustments of the atmospheric column and cloud dynamics, the net effect can be amplified considerably. We developed a technique to study the absorption of radiation of smoke over low lying clouds using satellite spectrometry. The TOA DRE of smoke over clouds is large and positive over the southeast Atlantic Ocean off the west coast of Africa, which can be explained by the large decrease of reflected radiation by a polluted cloud, especially in the UV. However, general circulation models (GCMs) fail to reproduce these strong positive DRE, and in general GCMs disagree on the magnitude and even sign of the aerosol DRE in the southeast Atlantic region. Our satellite-derived DRE measurements show clear seasonal and inter-annual variations, consistent with other satellite measurements, which are not reproduced by GCMs. A comparison with model results showed discrepancies with the Ångström exponent of the smoke aerosols, which is larger than assumed in simulations, and a sensitivity to emission scenarios. However, this was not enough to explain the discrepancies, and we suspect that the modeling of cloud distributions and microphysics will have the necessary larger impact on DRE that will explain the differences between observations and modeling.

INTRODUCTION

The absorption of radiation of smoke over low-lying clouds may be studied using satellite spectrometry with the newly developed differential absorption technique[1], see Figure 1. Aerosol absorption is strongest in the UV for smoke. Aerosols can significantly bias the retrieval of collocated clouds in a scene[2], therefore the cloud retrievals are performed in the shortwave Infrared (SWIR). These parameters are then used to compute the aerosol DRE at TOA.

The method was applied to Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) satellite observations from 2006–2009. In Figure 2a, a time series is shown of the SCIAMACHY aerosol DRE over cloud scenes averaged over the southeast Atlantic Ocean off the west coast of Africa, where the smoke plumes are most prominent. It clearly shows the progressing of the dry season, starting around June–July and ending around November. As the African continent becomes drier and drier, fires become more common, and the smoke absorbs the incoming solar radiation. This is expressed by high values of the aerosol DRE over clouds, which is positive in this region during the dry season.



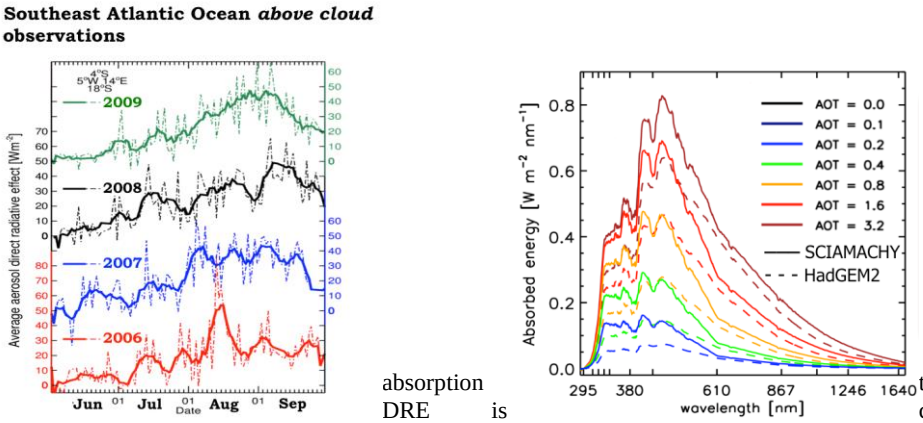


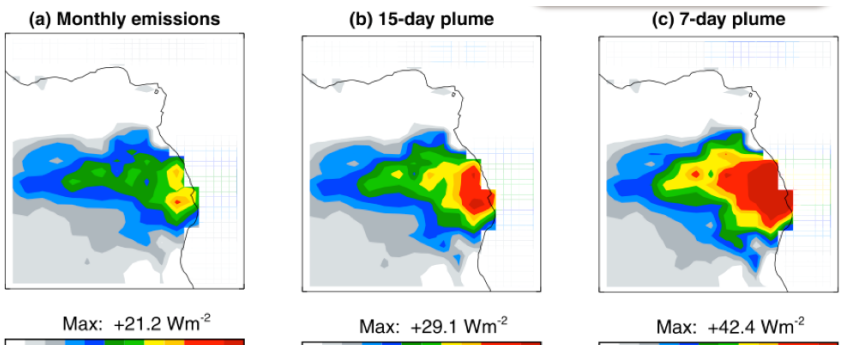
FIGURE 1. Differential aerosol absorption technique. The DRE is computed at TOA by comparing a measured scene with aerosols (green dots) and clouds (left panel) with an equivalent modelled cloud scene, without aerosols (right panel).

(a) **(b)**

FIGURE 2. a) Spatially averaged aerosol DRE over clouds between 5°W to 14°E and 4° to 18°S during June to September 2006–2009. b) Simulations of absorbed energy by the smoke model in HadGEM2 (dashed lines) and a smoke model that fitted the SCIAMACHY observations (solid lines) as a function of wavelength for different AOT at 550 nm as given. The simulated scene was a cloud with overlying smoke scene with the following set-up. Geometry: solar zenith angle = 0◦, viewing zenith angle = 30◦ and relative azimuth = 0◦; Surface: albedo = 0.05; Clouds: pressure = 925 hPa, droplet size r_{eff} = 8 µm, optical thickness = 20; Aerosols: pressure (AP) between 850 and 500 hPa.

RESULTS

General circulation models (GCMs) fail to reproduce the observed strong positive DRE, and in general GCMs disagree on the magnitude and even sign of the aerosol DRE in the southeast Atlantic region. Our satellite-derived DRE measurements show clear seasonal and inter-annual variations, consistent with other satellite measurements, which are not reproduced by GCMs. We compared our measurements with simulations from the UK Hadley Centre Global Environmental Model version 2 (HadGEM2) climate model[3]. A comparison with model results showed a discrepancy with the Ångström exponent of the smoke aerosols[4], which is larger (2.9 at wavelength below 400 nm) than assumed in simulations (1.45). This is illustrated in Figure 2b, where the absorbed energy as a function of wavelength in the model is compared to that of the observations. The spectral measurements from SCIAMACHY show a much stronger wavelength dependence of the absorption in the UV, which is not present in the model. In order to compare the observations and the model, the microphysical properties of the smoke model in HadGEM2 were changed in the UV to match the observations, keeping all else the same. The resulting absorption as a function of wavelength is shown in Figure 2b. The original smoke model consistently underestimates the absorption, especially in the UV. The larger Ångström exponent in the UV can be explained by the large fraction of Organic Carbon (OC) in African smoke. Changing the Ångström exponent of the smoke model matches the observations better in the UV. However, it could not explain the much larger average aerosol DRE values over the southeast Atlantic found in the observations. Therefore, the smoke emission scenarios in the model were changed to see whether this could explain the strong DRE. In the model, emissions are derived by linearly interpolating between monthly emission estimates from the updated Global Fire Emission Database biomass burning data sets, which prevents large changes in day to day emissions, while the observations clearly show short episodes of thick plumes. In Figure 3 the effect of a more episodic emission is illustrated. Figure 3a shows the aerosol DRE in the model for the period 1–8 August 2006 when the normal, linearly interpolated monthly emission estimates are used. In Figure 3b and 3c the same quantity is shown when the same amount of smoke is not emitted over the course of a month, but in 15 days (3b) or in a week (3c).



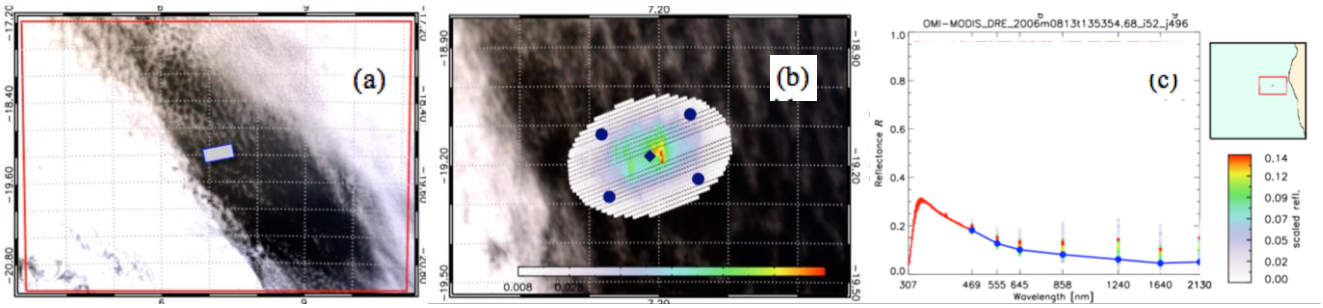


FIGURE 3. (a) HadGEM2 modeled cloudy-sky shortwave aerosol direct radiative effect in Wm^{-2}, averaged over 1–8 August 2006 at 9:30 local time for cloud cover larger than 0.3. The mean aerosol DRE over clouds for this experiment averaged over the whole month is 3.80 Wm^{-2}. (b) Same as Figure 4a but with emissions distributed over a 15 day period. Monthly mean is 5.94 Wm^{-2}. (c) Same as Figure 3a but with emissions distributed over a 7 day period. Monthly mean is 5.64 Wm^{-2}.

FIGURE 4. (a) Overview plot of the considered OMI pixel in a homogenous, (almost cloud-free) ocean scene; (b) MODIS reflectance at 469, convolved with the OMI PSF; (c) Combined spectrum in the UV/visible from OMI (red) and visible and SWIR from MODIS (blue) for the considered OMI pixel.

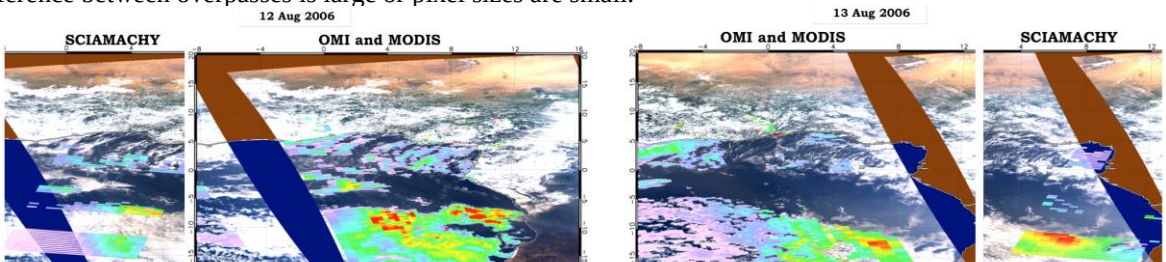
As expected, the maximum values increased considerably when thicker plumes were used during a shorter period, but it is still considerable lower than observed values. Furthermore, the aerosol DRE averaged over a month did not change much for different emission scenarios (numbers are in the caption of Figure 3).

Therefore, we conclude that the model is not able to reproduce the observed strong positive aerosol DRE over clouds, either instantaneously or in the monthly mean. We suspect that the modeling of cloud distributions and microphysics will have the necessary larger impact on DRE that will explain the differences between observations and modeling. Underlying clouds change the sign of the aerosol DRE, since aerosols will increase the planetary albedo of a dark ocean scene, but decrease that of a bright cloud scene. The resulting regional average will depend strongly on the correct simulation of the cloud distribution.

Since SCIAMACHY stopped delivering data, we have started to derive the aerosol DRE over clouds in the southeast Atlantic region by combining data from the Ozone Monitoring Instrument (OMI) and the Moderate-Resolution Imaging Spectroradiometer (MODIS). OMI provides measurements of the UV and visible reflectance at a moderate spatial resolution. MODIS provides reflectance at several spectral bands in the visible and shortwave infrared (SWIR) at a high spatial resolution. One spectral band is overlapping with OMI, which makes it possible to compare the reflectances and combine the spectra.

Figure 4 shows an illustration of the process of combining the reflectance spectra from OMI and MODIS. An OMI pixel has a spectral resolution of about 15x24 km^2 at nadir, increasing to about 42x126 km^2 at far off-nadir. OMI has no moving parts, but images the scene on a CCD. Therefore, an OMI field of view (FoV) typically is not quadrangular shaped, but rather is a super-Gaussian shape with soft edges, as illustrated in Figure 4. MODIS has a much finer spatial resolution of 1 km^2 or better. The OMI and MODIS observations can be combined by taking all MODIS observations within the OMI FoV and averaging them. In Figure 4, this is done for a mostly cloud-free scene, and produces a continuous spectrum from the UV to the SWIR. This can be used to estimate the aerosol DRE, since aerosols do not have spectral absorption features, and MODIS bands can be used to estimate the reflectance spectrum.

This method was used to produce aerosol DRE estimates over the southeast Atlantic region from OMI-MODIS spectra. Figure 5 show that there is good qualitative agreements between the observations from SCIAMACHY and OMI-MODIS for the strong smoke episode in August 2006. An obvious improvement is the much better spatial coverage of OMI and MODIS compared to SCIAMACHY and the higher spatial resolution. The accuracy of the method is strongly reduced when applied to instruments from different platforms, especially when the time difference between overpasses is large or pixel sizes are small.



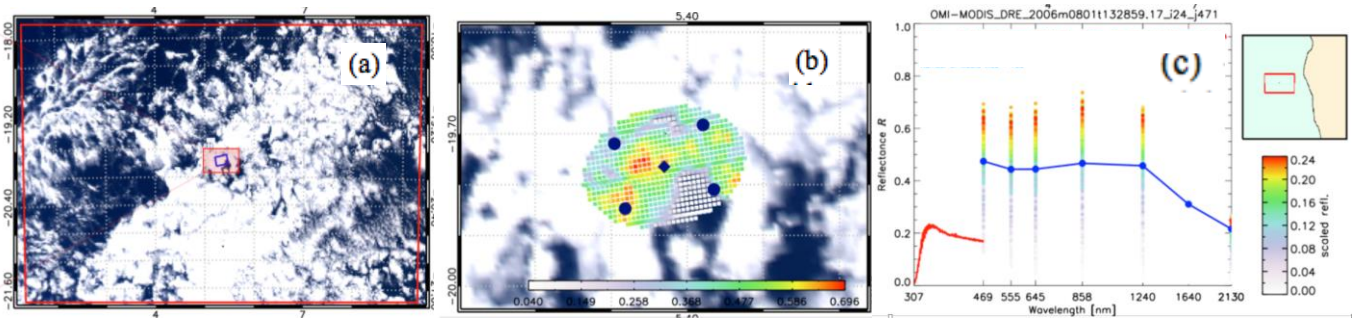


FIGURE 5. Instantaneous aerosol DRE over clouds on 12 (left panel) and 13 (right panel) August 2006 from OMI and MODIS, and SCIAMACHY (inset). Note that SCIAMACHY takes nadir measurements only half of the time (in blocks called states) and that it has a much narrower swath. SCIAMACHY measurements are taken around 10 AM local time in the descending node. Both OMI and MODIS measurements are taken around 2 PM in the ascending node. The time difference between OMI and MODIS observations is about 15 minutes.

FIGURE 6. (a) Overview of the considered broken cloud field (the red rectangle is shown in (b)); (b) MODIS reflectance at 469, convolved with the OMI FoV. (c) Spectrum in the UV/visible from OMI (red) and visible and SWIR from MODIS (blue) for the considered OMI pixel.

When broken clouds are in a scene, the scene can change significantly between overpasses, making a comparison or combination of OMI and MODIS challenging. This is illustrated in Figure 6, where the process of combining reflectances from OMI and MODIS in a broken cloud field is shown. The time difference between OMI and MODIS observations is about 15 minutes, and both instruments observe quite different scenes, making it hard to match the reflectance spectra.

CONCLUSIONS

The aerosol DRE can be derived for absorbing aerosols over clouds, using measured satellite derived reflectance spectra of aerosol-polluted clouds, and comparing them to radiative transfer modeled cloud scenes. Using this differential absorption technique, the aerosol DRE was successfully derived for the first time for smoke over the southeast Atlantic Ocean during the African dry monsoon season in 2006 using SCIAMACHY measurements. The measurements show that the DRE over clouds are larger than shown in global circulation models, while the models disagree between themselves about the sign and magnitude of the warming by absorbing aerosols. A sensitivity study showed that possible aerosol microphysical property assumption errors in the models are not sufficient to explain the lower model DREs. Also, different emission scenarios also could not explain the large discrepancies between simulated and observed DREs. The most obvious reason for the remaining differences are the representation of the clouds in the model, which have a strong impact on the TOA DRE. To further investigate the aerosol DRE over clouds, observations from OMI and MODIS were combined to apply the differential absorption technique to reconstructed spectra. This gives promising results with higher spatial resolution and better coverage than obtained from SCIAMACHY. However, the time lag between OMI and MODIS measurements reduces the quality of the reconstructed reflectance spectrum in the case of broken cloud scenes. Even though the time lag is only about 8 to 15 minutes, the scene brightness can be significantly changed due to cloud dynamics.

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