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Re-evaluation of dust radiative forcing using remote measurements of dust absorption

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ABSTRACT

Spectral remote observations of dust properties from space and from the ground creates a powerful tool for determination of dust absorption of solar radiation with an unprecedented accuracy. Absorption is a key component in understanding dust impact on climate. We use Landsat spaceborne measurements at 0.47 to 2.2 μm over Senegal with ground based sunphotometers to find that Saharan dust absorption of solar radiation is two to four times smaller than in models[1-3]. Though dust absorbs in the blue, almost no absorption was found for wavelengths > 0.6 μm. The new finding increases by 50% recent estimated solar radiative forcing by dust and decreases the estimated dust heating of the lower troposphere. Dust transported from Asia shows slightly higher absorption probably due to the presence of black carbon from populated regions. Large scale application of this method to satellite data from the Earth Observing System can reduce significantly the uncertainty in the dust radiative effects.

Dust, originating from natural sources and man-made soil disturbance, is the dominant feature in global maps of aerosol[4-6]. Its forcing of climate is important but highly uncertain[3]. Dust was shown to heat significantly the lower troposphere in the tropics[7]. The main uncertainty in the dust radiative effects is the dust absorption or single scattering albedo, ω_o (ratio of scattering to total light extinction)[3]. Models of dust optical properties are based on uncertain in situ measurements[8], with size dependent sampling efficiency[9], complex sample preparation, and deduction of the absorption from the sample reflectivity that depends on several weak assumptions[8]. Therefore, in situ absorption measurements tend to exaggerate the dust absorption[10]. Remote sensing techniques measure the properties of the undisturbed aerosol in the entire atmospheric column, relevant to aerosol direct radiative forcing of climate.

Dust absorption can be expressed by its imaginary index of refraction: n_i=-0.008 in models[11,12] (or ω_o=0.63 at 0.5 μm)[3]. Lower absorption was reported by Levin et al[13] of n_i=-0.003 (ω_o~0.87) for heavy dust. While in the blue and UV parts of the spectrum iron compounds can absorb sunlight[8], the absorption in the visible may originate probably only from black carbon absorption[8,14] from urban pollution or biomass burning smoke mixed with the dust. This absorption by Saharan dust, measured in situ, contradicts published results of radiance measurements. Flux divergence measured from aircraft[15] reports ω_o=0.95 for broad solar spectrum. Analysis of Landsat data derived imaginary index indistinguishable from zero[16] (n_i=-0.001±0.001) at 0.55 to 0.86 μm. Ackerman and Chung[17] found that measured value of ω_o = 0.75 would incorrectly predict that dust should reduce ERBE measurements of the reflected solar flux over bright desert. Here we improve on previous satellite techniques[16,18] by combining satellite and ground based remote measurements[19,20] and extending the spectral range to 2.2 μm.

The remote sensing method is illustrated in Fig. 1. For dark surface (ocean), dust increases the apparent reflectance of the earth + atmosphere system, with only small dependence on ω_o. For brighter surfaces (reflectance of 0.25), ω_o determines if the dust will increase or decrease the apparent reflectance. The sensitivity is even higher for brighter desert surfaces. Over a bright surface dust can absorb the direct solar radiation and radiation reflected from the earth surface, increasing the absorption efficiency. This mechanism depends on the size of dust particles and their optical properties.

To derive the dust size distribution we use sky aureole radiance measured by the AErosol RObotic NETwork (AERONET)[19]. Measurements from Capo Verde, west of the Sahara and Sede Boker, Israel, east of the Sahara show that dust size distribution is dominated by a coarse mode with effective radius between 1.5 and 2.5 μm[20]. Similar results were reported from aircraft measurements[21] and models[1]. In Capo Verde, a smaller coarse mode, 0.4-0.5 μm, is also present. Dust scattering efficiency of 0.83 m^2/g measured by Li et al.[6] on the western side of the Atlantic ocean in Barbados correspond to effective radius of 1 μm; smaller, as expected from the values of 1.5-2.5 μm used here closer to sources. AERONET measurements of Asian dust arriving across the Pacific Ocean to San Nicholas island, off the west coast of US shows effective radius of 1.5 μm.

Knowing the size, dust absorption is derived from simultaneous Landsat images and sunphotometer measurements in Senegal[22]. For the sun-view direction, the dust scattering angle is 148° - thus we do not expect significant effects of particle nonsphericity[23,24]. Data from May 3, 1987 are used as the less dusty - "clear" day (sunphotometer optical thickness at 0.64 μm of τ_{64}=0.8) to derive the desert reflectance, ρ. Then ρ, is used to calculated the expected apparent reflectance, ρ^*_c, in the dusty day (τ_{64}= 2.4) for several values of ω_o and compared with the measured apparent reflectance in the dusty day, ρ^*_m (Fig. 2A). Spectral dust absorption is determined by fitting the measured radiance to the calculated one for each channel. To explain the increase in the earth-surface reflectance of 0.06 due to the presence of dust a close to zero absorption has to be used. Even n_i=-0.004 (ω_o=0.83 at λ=0.65 μm) would cause a decrease rather than increase in the apparent reflectance (Fig 2A). Uncertainty in the effective radius or real part of the refractive index result in uncertainty of only Δn_i=±0.0005 or $\Delta\omega_o$=±0.005 (Fig. 2B). The results are compared with the literature. Note that while the increased absorption in the blue channels is expected due to the presence of iron oxides in hematites[3], the small absorption at 1.65 μm is surprising, but found already in the spectra of Mars, due to mineral-hydrate mixtures[25].

Landsat data over the ocean serve as a consistency check to the dust model (Fig. 2C). The measured spectral apparent reflectance is similar to the calculated values for the clear and dusty days. Real part of refractive index, n_r=1.22 at 2.1 μm[12], cannot explain the measurements. Therefore index n_r=1.46 for 1.65 and 2.1 μm is used. For short wavelengths there is only weak sensitivity to n_r due to the large ratio between the effective particle size and the wavelength, and n_r=1.53 is used. What other sources of errors, except for uncertainty in the dust particle size and nonsphericity can affect the results? Surface angular effects are expected to be negligible for the nadir view[26]. The uncertainty in the calibration of the sensor of ~10%[27], has a small effect since dust absorption is derived from the difference between the dusty and less dusty day. Calibration error of 10% causes an error of $\Delta\omega_o$=±0.001.

On April 25, 1998 a dense plume of Asian dust arrived at San Nicholas island along the California coast. Optical thickness of τ_{64}=0.4 was measured simultaneously with a Landsat image. The corresponding clear day (τ_{64}=0.05) was April 9, 1998. This dataset provides the opportunity to compare the results to non-Saharan dust. The island is vegetated, thus surface reflectance for λ<0.8 μm is too low to derive ω_o. For λ=0.86 and 1.65 μm we found ω_o= 0.93 and 1.00 respectively. This large spectral change, beyond the lower accuracy limits in this case ($\Delta\omega_o$=±0.02) due to the smaller dust opacity, results probably from an external mix of black carbon from urban activity in east Asia and dust.

Dust affects the energy balance of the earth both in the solar spectrum and in the IR[1-3]. The solar radiative forcing at the top of the atmosphere is very sensitive to absorption by dust. Tegen et al.[1], used a model with n_i=-0.006i at 0.55 μm (ω_o=0.85). They found that dust from man-made soil disturbance extract a globally averaged forcing of -0.25w/m^2 in the solar spectrum. The present ω_o=0.97 at 0.55 μm scaled across the solar spectrum, produces 2-3 times less absorption and magnifies the solar forcing by 50% to -0.40 w/m^2. Sokolik and Toon[3] used single scattering albedo of ω_o=0.85 at 0.50 μm to calculate a representative value of radiative forcing of -0.25 w/m^2 over the land and-0.6 w/m^2 over the ocean. Our lower dust absorption increases the forcing to -0.65 and -0.75 w/m^2 respectively, similar to that of sulfate or smoke aerosol[3]. The uncertainty range[3], mainly due to uncertainty in the strength of the sources, would change to -0.2 to -2.0 w/m^2, thus can be comparable but of opposite sign to the total greenhouse forcing. The impact of the new finding on the radiative forcing calculations is summarized in Table 1. The lower dust absorption increases significantly the dust forcing at the top of the atmosphere. The IR forcing, not discussed here, was shown to mitigate a third to half of the solar forcing[17,28].

We were able to determine the dust properties using a few coordinated Landsat images, acquired in advance, with ground based measurements. Several publications were shown to indicate that the derived low dust absorption can be representative for Saharan dust. The global data availability will improve by several orders of magnitude with the launch in 1999 of the MODIS instruments on the Earth Observing System with 8 solar bands[29,30], the CERES instrument for radiative flux measurements[31,17,32] and the measurements of 100 AERONET ground based sun/sky radiometers[19]. With these measurements we expect to be able to characterize the global climatology of dust optical properties and to decrease the uncertainty in dust effect on climate due to better characterization of the rate of dust emissions and their radiative properties.

Acknowledgment

The AERONET sunphotometer/radiometer data were provided by Brent N. Holben from GSFC, Robert Frouin from Scripps, F. Lavenu from CESBIO/CNES/CNRS in Toulouse and B. Chatenet from LISA/Universités Paris 7 and 12. We are thankful for comments by Ina Tegen from NASA/GISS, Irina Sokolik and Brian Toon from U. Colorado and Zev Levin from Tel Aviv U.

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Table 1: Effect of the smaller dust absorption found in this study on the dust radiative forcing in the solar spectrum. Note that the global estimates for ref. [3] assumed an equal coverage of land and ocean in the dust belt.

Reference	Land	Ocean	Global
Tegen et al.[1]			-0.25w/m^2
same but with present smaller absorption			-0.40 w/m^2
Sokolik and Toon[3] representative value	-0.25 w/m^2	-0.6 w/m^2	-0.42 w/m^2
same but with present smaller absorption	-0.65 w/m^2	-0.75w/m^2	-0.70 w/m^2
Sokolik and Toon[3] uncertainty range	-0.08 to -0.9 w/m^2	-0.2 to -2.2 w/m^2	-0.1 to -1.5 w/m^2
same but with present smaller absorption	-0.2 to -2.3 w/m^2	-0.2 to -2.7 w/m^2	-0.2 to -2.5 w/m^2

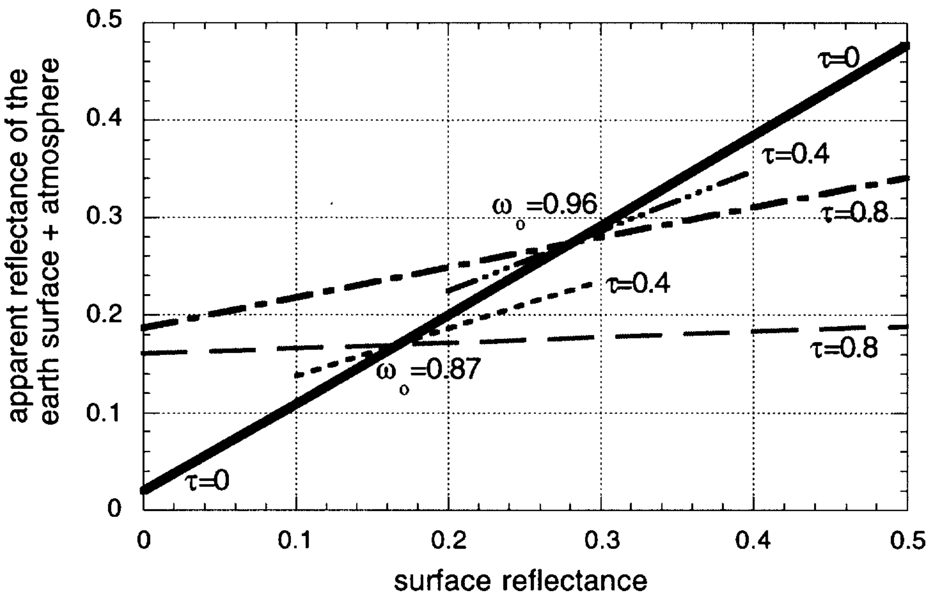
Legends for figures:

Fig. 1: The apparent reflectance of the earth surface as observed from space and influenced by the atmosphere at 0.66 μm. Solid line - no dust (τ=0) only molecular scattering, broken lines - dust with low absorption, ω_o=0.96, and high absorption, ω_o=0.87, respectively. Optical thickness, τ, of 0.4 and 0.8 is indicated. The concept was explored by Fraser and Kaufman[32].

Fig. 2: (A): Apparent reflectance at the top of the atmosphere over the desert measured by Landsat TM (heavy gray lines) for optical thickness of 0.8 (dashed) and 2.4 (solid). The measurements are compared with calculations (thin black lines) for refractive indices and effective radius given in the caption. The apparent reflectance increased due to the presence of dust by ~$\Delta\rho$=0.06 (for the central spectral range of 0.55-1.6 μm) despite the high surface reflectance of 0.2 to 0.4. Calculations for imaginary index of -0.004 cannot explain this change in the apparent reflectance, indicating small or no absorption.

(B): The spectral single scattering albedo, ω_o, for the two values of the effective radius, that fit the change in the brightness in Fig. 2A (ω_o=1 - non-absorbing dust and ω_o=0 - fully absorbing). For comparison ω_o values derived or used in the literature are given: F - Fouquart et al.[15], W- WMO[12], T- Tegen et al.[1], C - Carlson and Benjamin[2], S - Sokolik and Toon[3].

(C): Apparent reflectance, as in Fig. 2A but over the ocean, for the absorption indicated in Fig. 2B and several values of real refractive index and effective radius. The real part of the refractive index is kept constant or decreasing to 1.22 at 2.1 μm.



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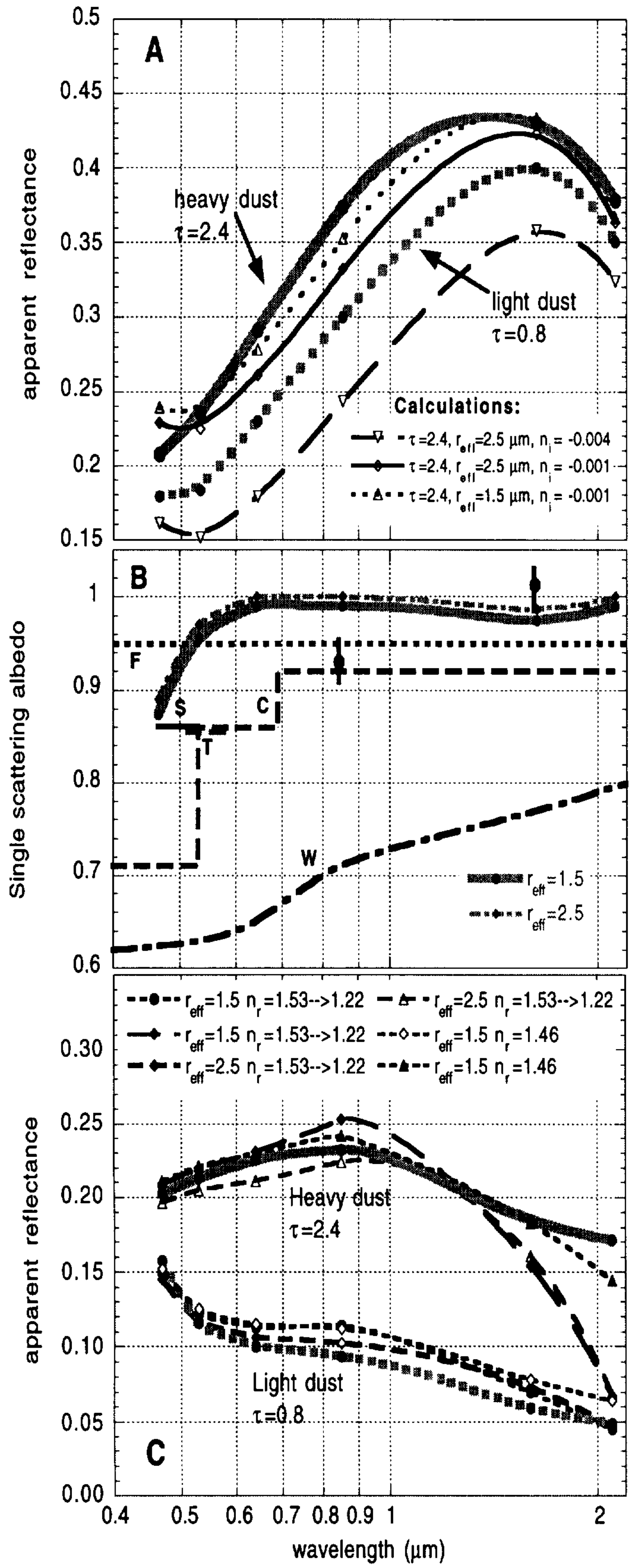

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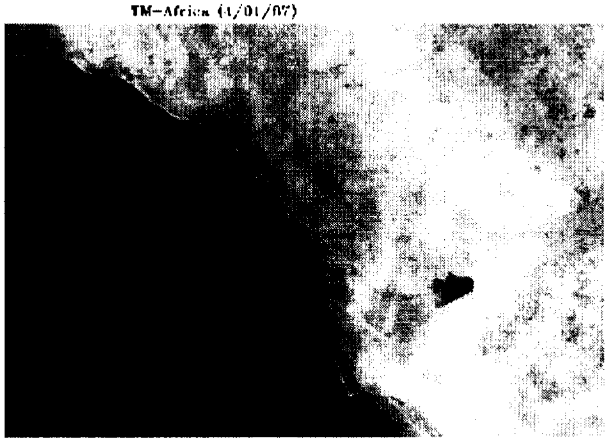
Suggestion for cover of the issue:

April, 1, 1987

TM-Africa (4/01/87)



April, 17, 1987

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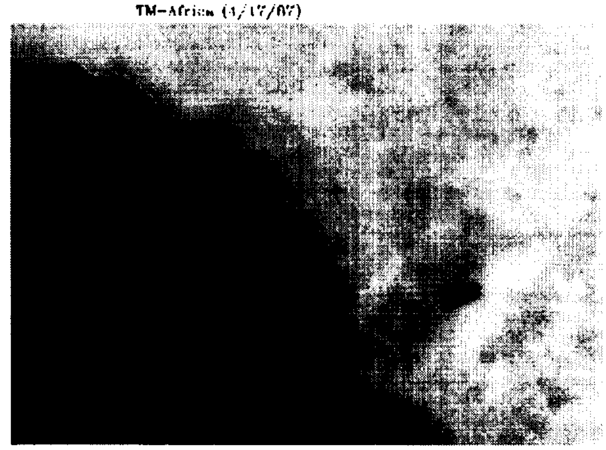

Cover: Color composite of the two dusty Landsat TM satellite scenes. Heavy and variable dust was measured April 1, 1997 and uniform heavy dust on April 17, 1987. The scenes are used to derive the dust properties and radiative forcing of climate.