Radiative heating rates profiles associated with a springtime case of Bodélé and Sudan dust transport over West Africa

Author(s): C. Lemaître et al.
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Reply to the Referee 1

We thank the reviewer for his/her helpful corrections and thoughtful suggestions on our previously submitted manuscript. All comments have been taken into account when producing the revised manuscript.

1- *This is what I would suggest anyway: Leave out the cloudy profiles. This also avoids trouble with possible 3D-effects not accounted for in the STREAMER simulation:* Heating rates were computed indifferently in cloud-free conditions and in the presence of low-level clouds, in spite of the fact that STREAMER might not be able to account for three-dimensional effects induced by clouds. This choice was motivated by the fact that the liquid water content associated with the cumulus clouds was rather small (on the order of 0.05 g m^{-3} and that the albedo associated with these clouds is comprised between 0.2 and 0.4 (Fig. 1). Ultimately, the relevance of this approach was assessed by the fact that, at a given altitude, coherent HRs were obtained for contiguous profiles, independently of the presence of cumulus type clouds.

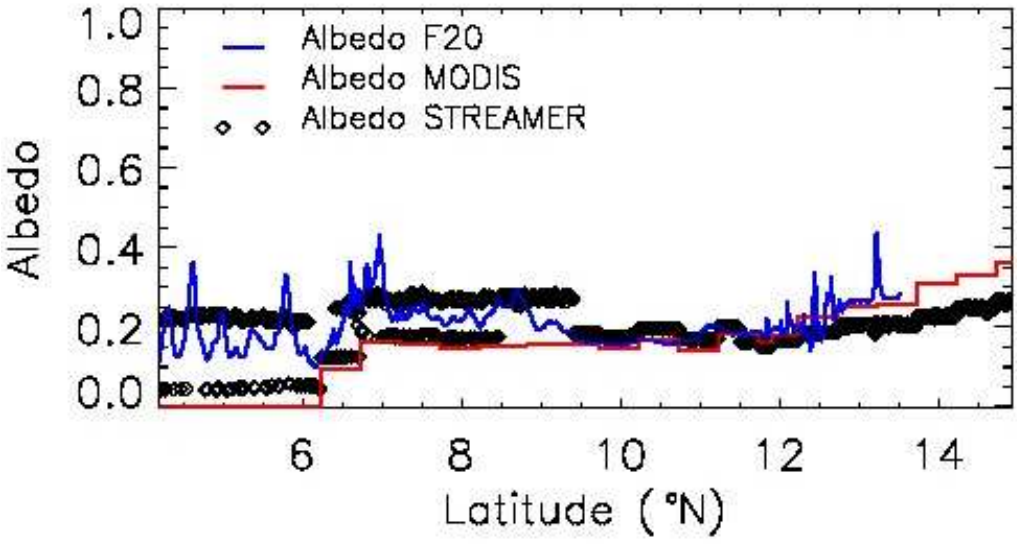


Figure 1: Surface shortwave albedo from MODIS (red line) derived along the F/F20 flight track on 14 June 2006. Superimposed are the total effective albedo (accounting for the surface, aerosol and clouds) obtained from shortwave downwelling and upwelling airborne irradiances (blue line) and from STREAMER-simulated irradiances (dark diamonds).

2- *The terms "radiative forcing" and "heating rates" should more clearly be defined in Section 3. The best is to give the respective equations and the assumptions made Also please indicate the wavelength range covered and add "net" if these two terms combine both the solar and terrestrial spectral ranges.:* To clarify this aspect of the

paper, we have added a discussion on the terms in section 3 **"The radiative code"**, together with equations. The following texte has been added:

"Vertical profiles of aerosol radiative heating rate over West Africa are quantified using the radiative transfer code STREAMER (Key, J. and Scheiger, A. J., 1998, Key, J., 2001). STREAMER is a flexible code developed to compile radiances or irradiances for various atmospheric and surface conditions. Calculations are made using a 2 stream scheme with a discrete ordinate (DISORT) solver. Upward and downward irradiances (i.e. shortwave, longwave and net irradiances (see equation 1)), cloud radiative effect ("cloud forcing"), and heating rates (HR) can be computed over 24 shortwave bands (0.28 to 4 µm) and 105 longwave bands (4 to 400 µm).

The net irradiance (0.2 to 500 µm) can be written as:

$$F_z = F_{dir,z}^{\downarrow} + F_{diff,z}^{\downarrow} - F_{diff,z}^{\uparrow} - F_{em,z}^{\uparrow} \quad (1)$$

where $F_{dir,z}^{\downarrow}$ is the direct downward irradiance, $F_{diff,z}^{\downarrow}$ is the diffuse downward irradiance, $F_{diff,z}^{\uparrow}$ is the diffuse upward irradiance, $F_{em,z}^{\uparrow}$ is the upward emitted irradiance and z is the altitude .

In the present study, the radiative forcing (i.e. heating or cooling) is calculated from a pair of STREAMER simulations, i.e. as the difference between a dust-laden and a dust free simulation (see Eq. 2). The total radiative forcing in the shortwave (longwave) part of the spectrum is computed as the integral of the forcing over the 24 (105) bands.
The radiative forcing is given by:

$$\Delta F = F_{d,z} - F_{0,z} \quad (2)$$

where $F_{d,z}$ and $F_{0,z}$ are the net irradiance in the presence of dust and without dust, respectively.

Heating/cooling rates are computed for each layer, and are based on finite difference estimates of the irradiance divergence at each pair of levels (Eq. 3):

$$\frac{\Delta T}{\Delta t} = -\frac{g}{C_p}\frac{\Delta F}{\Delta p} \quad (3)$$

where T is temperature (K), t is time (s), g is gravitational acceleration (ms^{-2}), Cp is the specific heat of dry air (JK^{-1} kg^{-1}), F is the net all-wave flux (Wm^{-2}), and p is the pressure (Pa). The gravitational acceleration is computed for each level from an empirical relationship derived for a standard atmosphere. Computations are begun at the top of the atmosphere. Layer heating/cooling rates are converted to degrees per day and are listed with the level that is their top. Therefore the surface level has a value of zero."

3- *Maybe it would be wise to separate the "net heating rates" into their solar and terrestrial portions.* This is done in Section 5.3.4 when we discuss the importance (or lack there of) of the longwave contribution to the total or net heating rates.

4- *Also state that the "net heating rates" are no instantaneous values rather than 24-hour averages.* In fact, we are dealing with instantaneous heating rate which has been calculated by the following equation: $\frac{\Delta T}{\Delta t} = -\frac{g}{C_p}\frac{\Delta F}{\Delta p}$. The heating rate is expressed in terms of K/day. However we have performed such calculations for both daytime cases and nighttime cases. This suggests how the heating rates tend to evolve during a

typical day over West Africa. We hope that this is clearer now that we have introduced the equation.

5- *Do they contain both the molecular and dust effects or is the dust influence separated?* As detailed in the point 2: in this paper heating rate only contains the dust effect. Molecular contributions have been removed from the net heating rate values.

6- *What is always good to pinpoint the radiative simulations would be to compare the irradiances (basis for the forcing and heating rate simulations) from the model with those measured on the aircraft, or -if such in situ airborne radiation data are not availablewith ground based data collected during overflights. I wonder if the authors have such data to be compared and thus to increase the trust in their radiative calculations. I suggest to modify the title of the manuscript to:"Radiative heating rate profiles associated with a springtime case of Bodele and Sudan dust transport over West Africa*. A new section called "**Comparison of irradiances and surface/cloud albedo from the model with measurements**" has been incorporated to presented a validation of longwave & shortwave, upwelling/downwelling irradiances associated with dust and simulated with STREAMER. Comparison is made with surface radiometer measurements (in Wankam, Niger) and onboard the Falcon 20. The following Figure as been to the paper.

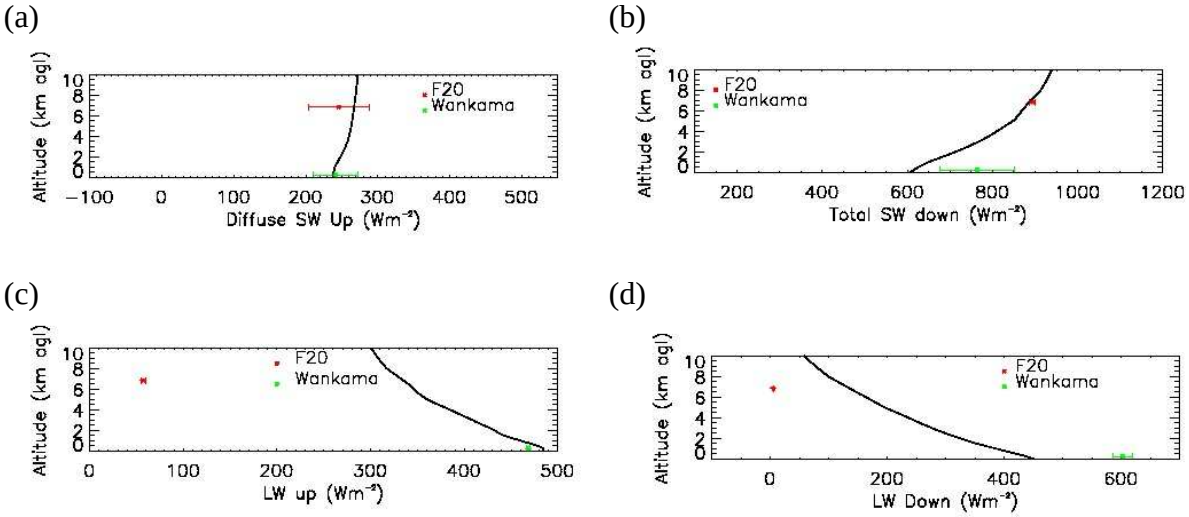


Figure 2*:* Comparison between irradiances profiles derived from STREAMER (black solid line) obtained at the location of the Wankama station and at the time of the F/F20 overpass on 14 June. The data from the F/F20 are in red and data from the Wankama station are in green: upward shortwave **(a)** downward shortwave **(b)**, upward longwave **(c)** and downward longwave **(d)**.

7- *The abstract contains several acronyms (STREAMER, LEANDRE, CALIOP, MODIS) which are not explained in the abstract. This should be avoided.* STREAMER and AVIRAD are not acronyms. LEANDRE (Lidar Embarqué pour l'étude de l'Atmosphère: Nuages Dynamique, Rayonnement et cycle de l'Eau), CALIOP (Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations), MODIS (Moderate-resolution Imaging Spectroradiometer) have been explained in the abstract.

8- *Line 32-33: Line 32-33: What is meant with "... large enough to modify the low tropospheric equilibrium." ?* This unclear sentence has been removed from the revised version of the paper.

9- *Line 48: It is known in the community that a second SAMUM campaign has been performed based on Cape Verde. That should be mentioned here.* The second SAMUM campaign is now mentioned in the paper and the reference to Weinzierl et al. (2008) has been added.

10- *Line 50: WAM is a not explained acronym (even if obvious what it means it needs to be explained).* WAM (West African Monsoon) is now explained.

11- *After line 59 it would be good to say something on the discussion of dust influence on hurricane activity, something which is kind of expected here.* We have added the following sentence: « Saharan dust that crosses periodically the Atlantic between 1000 and 5000 m is also thought to play a role on the genesis and the evolution of tropical cyclones as suggested in recent studies (Dunion and Velden, 2004, Evan et al., 2006).»

12- *Line 125: The BER values applied here should be somehow justified in more detail. This is something very crucial, also because in other occasions (line 200) the authors apply other values. Also it would be good to justify why a constant value is applied in the first case, whereas the BER was allowed to vary with hight later on (maybe I am wrong on this).* We have clarified these aspects in the revised version. The BER is not assumed wavelength independent. BER has been calculated at the lidar wavelength for both LEANDRE and CALIOP instruments following the climatology given by Omar et al., (2009). In all cases, we used constant profiles of BER with the values corresponding to the desert dust climatology used for CALIOP (described in Omar et al, (2009) interpolated at 730nm for airborne lidar and at 532 nm for CALIOP. However, differences in the multiple scattering effects between the airborne and spaceborne lidars are accounted for through the so-called multiple scattering coefficient η. We neglect these effects when analysing data from the LEANDRE system (η=1) and we use a η profile obtained from MonteCarlo simulations (Young et al., 2008) for CALIOP. This discussion is now included in the manuscript as:

In section 2.2

" LEANDRE-derived aerosol extinction coefficient (AEC) profiles (at 730 nm) were obtained from the total attenuated backscatter coefficient (TABC) profiles, via a standard lidar inversion technique (Fernald et al., 1972; Fernald et al., 1984), with a vertical resolution of 15 m and a horizontal resolution of roughly 500 m. This inversion technique relies on the proportionality of the aerosol backscatter coefficient (ABC) and AEC, i.e. ABC (z)= BER x AEC (z), BER being the aerosol backscatter-to-extinction ratio and z the altitude. We considered that BER is constant with altitude (e.g.; Welton et al., 2000) and we used a value of 0.02 sr-1, which is a climatological value for dust (Omar et al., 2009) interpolated linearly at 730 nm between values provided at 532 nm (0.024 sr-1) and 1064 nm (0.018 sr-1). The molecular backscatter coefficient profiles used in the inversion procedure were obtained from dropsonde-derived pressure and temperature measurements. In the lidar inversion, multiple scattering effects may be considered by introducing a so-called multiple scattering factor η ($0 \leq \eta \leq 1$) to account for the reduction of the effective aerosol extinction coefficient η AEC(z) (e.g., Nicolas et al., 1997). In the case of dust particles, this

effect can be neglected ($\eta \approx 1$) for airborne lidar measurements (Ackermann et al., 1999) since the volume of air sampled by the lidar beam is sufficiently small (note that the laser footprint on the ground is ~3.5 m wide). Because of the uncertainties on the value of the BER, the sensitivity of dust-related heating rates will be conducted thereafter (see Section 5)."

In section 2.3

"CALIOP-derived aerosol extinction coefficient (AEC at 532 nm) profiles were obtained from our own calculation (using level 1B version 2), with a vertical resolution of 60 m and a horizontal resolution of roughly 12 km. To obtain AEC from TABC profiles, we use the same lidar inversion technique as for LEANDRE 2. The molecular backscatter coefficient profiles used in the inversion procedure were obtained from molecular density profiles extracted from the National Centers for Environmental predictions (NCEP) analyses along CALIPSO tracks. We use a constant BER profile at 532 nm with a value of 0.024 sr^{-1} (Omar et al., 2009). Since CALIOP samples a sufficiently large volume of air (the footprint at the ground is 90 m wide), we considered here a multiple scattering coefficient η for dust particles below one. Following the MonteCarlo simulations of Young et al., (2008) and Berthier et al., (2006), we used a η profile increasing exponentially from 0.65 at the layer top, 0.87 below 500 m above ground level (a.g.l.) and to 0.95 at the ground, as in Cuesta et al. (2009) and Messager et al. (2010)."

13- *Line 150: Size distributions based on non-absorbing refractive index from the calibration particles seem to make little sense. Can you please discuss this issue in more detail?* The author is right. Size correction of GRIMM data depends on the effective aerosol refractive index, and can result in important modifications in the position of the size bins, in particular when the aerosol is absorbing (Collins et al., 2000). However, when this is not determined in a robust way, the correction itself can induce important errors. Nonetheless, we have performed Mie calculations using the refractive index estimated by the "Raut and Chazette" and the "Chomette et al." models at 780 nm (1.53 – 0.008i and 1.53 – 0.0012i, respectively) to calculate the correction factor to be applied to the GRIMM nominal diameters. The correction factor is important, up to a factor of 2 for particles larger than 4.5 µm in diameter. As a consequence, the asymmetry parameter g increases of 6% independently of the wavelength. These new values are now shown in Figure 4 of the paper.

14- *Line 163: What the author call a "fair agreement" in Figure 2, is in my opinion actually a "blunt disagreement". In Figure 2 the vertical axis should be linear; the percentage differences should be plotted. Also I would like to know how the AVIRAD-beta values have been obtained, the assumptions made would be good to know.* We agree this may not have been very clear. The discussion has been modified substantially as follow. The Figure (see below) has also been modified.

"Figure 2 shows a comparison between the LEANDRE-derived scattering coefficient (at 730 nm) and the AVIRAD-derived scattering coefficient at 700 nm at an altitude of 700 m msl. For the comparison, the lidar-derived scattering coefficient is divided by a factor of 14 (the reason for this is explained below). The LEANDRE-derived scattering coefficient (between 0 and 180°) is computed as the product of the AEC by the SSA, after screening most cloudy profiles. The SSA value used here is derived from the AVIRAD observations along the legs of interest. By construction, the AVIRAD scattering coefficient is obtained between 90 and 180°. The ratio between

the scattering coefficient between 0 and 180° and the scattering coefficient between 90 and 180° was computed using Mie theory for spherical particles based on AVIRAD observations and two dust aerosol models (described at length in Section\{sec3}). This ratio was found to be equal to 12 in one case and 16 in the other case, thereby yielding a value of 14±2. Hence, the scattering coefficient derived from LEANDRE 2 is expected to be on the order of 14 times that derived from AVIRAD.

When modeling the aerosols as non spherical shapes rather than spherical particles, small differences were found between the results from the Mie model with spherical particles and Mishchenko T-matrix code (Mishchenko et al., 1996) using prolate and oblate particles uniformly distributed over all the possible aspect ratios centered around 1 (1% error on the SSA and the extinction coefficient). Mishchenko et al. (1996) suggested that this phenomenon can occur when large numbers of randomly orientated particles in the sampling chamber are averaged, leading to a smaller error than for individual particle counting. It may be also due to the uncertainties in our measurements, especially of size distribution, and the lack of knowledge on dust morphology.

As shown in Fig. 2, the scattering coefficient derived from AVIRAD and from LEANDRE (divided by 14) exhibit similar fluctuations as a function of latitude, with a minimum between 10.1 and 10.3°N. Provided that a reduction by a factor of 14 is applied to the lidar data to account for the different observation geometry of the instruments, a very good agreement is found in terms the scattering coefficient obtained with LEANDRE~2 and AVIRAD. This is an indication of the coherence between the two datasets."

15- *In 2.2.3 you should also refer to the following paper: Bierwirth, E., M. Wendisch A. Ehrlich, B. Heese, M. Tesche, D. Althausen, A. Schladitz, D. Müller, S. Otto, T. Trautmann, T. Dinter, W. von Hoyningen-Huene, and R. Kahn, 2009: Spectral surface albedo over Morocco and its impact on radiative forcing of Saharan dust. Tellus, 61B, 252-269, DOI: 10.1111/j.1600-0889.2008.00395.x..* The paper Bierwirth et al. 2009 has been included..

16- *Line 265: Please replace "flux" by either "flux density" or even better by "irradiance". Replace "flux" in the entire text.* In the entire text "flux" has been replaced by "irradiance".

17- *4.1 could be significantly shortened, not really important.* This part is already short and we believe it is important to provide some synoptic background to the reader.

18- *As already mentioned, stay away from clouds. Anyway, with a liquid water content of 0.05 g m-3 one can hardly call this a cloud. Another problem seems to me that an average cloud has been assumed, although these clouds are always highly variable.* See answer to your comment #1.

19- *Surface albedo was handled as a broadband one, one number for all spectral bands. Is this something the authors worry about in the spectral simulations?* A short paragraph about surface albedo has been written in the section 3. "Radiative code" after the paragraph about gaseous absorption:

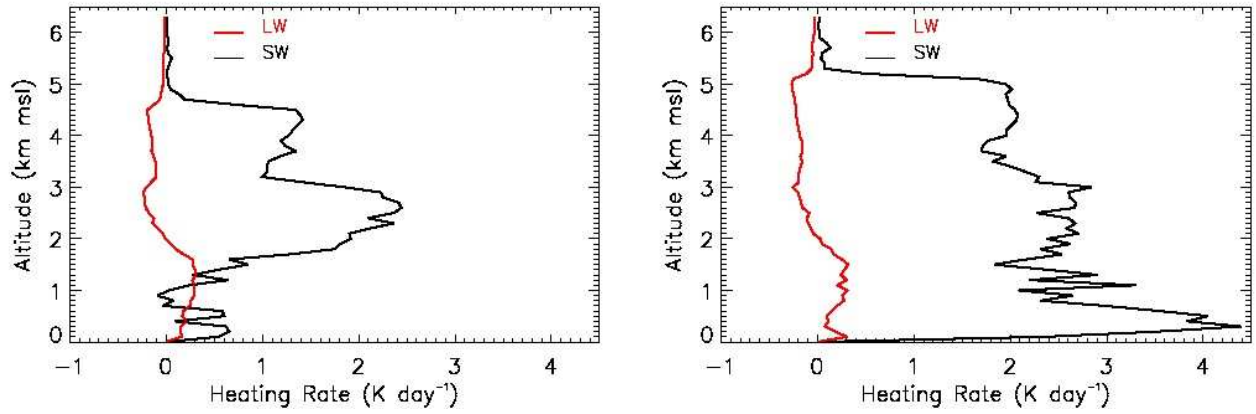
"For the surface albedo a built-in spectral albedo model prescribed in STREAMER is used, but it is scaled by a user-specified visible albedo determined using MODIS data for the surface types present. The surface albedo models available in SREAMER are based on either modeled or observed data in the literature. Sand data are from Tanre et al (1986). Spectral albedos for grass, dry grass, and deciduous forest were taken from the ASTER Spectral Library v1.0 CD (1988, California Institute of Technology). This spectral dependence of surface albedo is representative of MODIS measurements acquired in this region (Raut et Chazette, 2008)"

20- *Omit reference "in preparation", e.g., Formenti et al. (2010)*: This paper will be submitted in ACP before the end of the year.

21- *Some Figures are of poor quality (e.g., Fig. 3). Axis labels should be clearly readable. In general the number of Figures could (should) be reduced.* Some of Figures have been redrafted to be clearer.

22- In the original version of the paper, we have discussed the importance of the infrared part of the spectrum (0.7-400 µm) to the heating rate. In the revised version of the manuscript, because we are comparing irradiance profiles with radiometry measurements in the longwave and shortwave domain, we have modified our approach to the discussion on the contribution of infrared/visible to the total heating rate retrievals. We are now considering the shortwave/longwave domains rather than the visible/infrared domains. This when we are also more in line with previpus studies which have attempt to address the partition between longwave and shortwave rather than infrared/visible. In the revised version of the manuscript, we consider the longwave domain to extend from 4 to 400 µm. The following Figure has been added (which replaces the previous one), together with a discussion.

(a) (b)



(c)

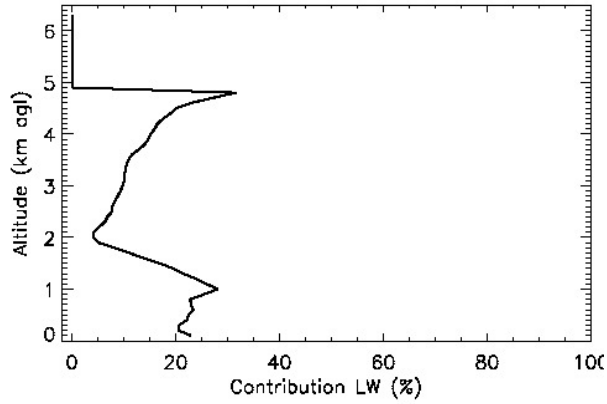


Figure 3 : Heating rate profiles in the longwave domain (red solid line) and in the shortwave domain (black solid line) derived from LEANDRE 2 at 10°N (a) and 13°N (b) with the RaCH model. (c) Relative contribution of the longwave to the total heating rate averaged along the entire F/F20 transect on 14 June.

References (added in the revised version of the manuscript)

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