Clear-sky Atmospheric Radiative Transfer: A Model Intercomparison for Shortwave Irradiances

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Abstract. This study consists of an intercomparison of clear-sky shortwave irradiances calculated by the Doubling Adding model of KNMI (DAK) and the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS). The DAK and SMARTS models are run with identical input (state profiles, water vapour, ozone, aerosols, etc.) and the differences between the models are examined in terms of broadband shortwave irradiances as a function of solar zenith angle. The DAK and SMARTS models agree very well. For a pure Rayleigh atmosphere the differences in the irradiances are less than 5 W/m^2. For cases with aerosols the differences of the irradiances are within 10 W/m^2.

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INTRODUCTION

Lots of efforts have been made to achieve agreement between clear-sky shortwave irradiance measurements and model simulations. In a recently published paper by Michalsky et al.[1] six radiative transfer models are used to compare the direct and diffuse horizontal broadband shortwave irradiance measurements at the Southern Great Plains site during a large aerosol intensive observation period in May 2003. The SMARTS model (the Simple Model of the Atmospheric Radiative Transfer of Sunshine) is one of the models that participated in the comparison. The authors find that the biases between modeled and measured direct irradiances are in worst case 1%, and biases between modeled and measured diffuse irradiances are less than 1.9%. The range is within the estimated uncertainty in the direct (8-12 W/m^2) and diffuse irradiance measurements (4 W/m^2). This result is much better than previous clear sky closure studies. The authors think that the good agreement is due to better specification of input parameters and better measurements of irradiances.

It is more difficult to achieve shortwave closure between model and measurements for cloudy cases. The cloud optical properties have to be properly characterized to produce a good input for the model. Then the radiative transfer model should have the ability to treat the cloud properties efficiently. The line-by-line version of the DAK model (Doubling Adding KNMI) has been widely used in cloud, aerosol and trace gas retrievals in KNMI. The advantage of the DAK model is that it can compute multiple scattering in clouds accurately[2,3]. Recently the DAK model has been made suitable for broadband calculations using the correlated k-distribution method for gaseous absorption[4]. Therefore we plan to use the DAK model for broadband shortwave radiative closure studies for cloudy cases in addition to the clear-sky cases.

In this paper, firstly we will describe the DAK model and the model setup for the comparison. Secondly, we will describe the results of the model comparison for clear-sky shortwave irradiances without aerosols. Thirdly, the results of the model comparison with LOWTRAN aerosols will be presented and discussed. Last section of the paper is conclusions and future work.

DAK AND SMARTS MODEL SETUP

The DAK model uses the doubling-adding method to calculate upward and downward radiation at every interface of a multilayer plane-parallel atmosphere. It includes multiple scattering, polarization, and different kinds

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of phase matrices for cloud and aerosol particles. At large solar zenith angle (SZA) pseudo-spherical correction is included. The original version of the DAK model is a line-by-line code, covering wavelengths from UV to near-IR. Up to seven gases, O_3, NO_2, H_2O, O_2, BrO, SO_2 and O_2-O_2, can be taken into account in the DAK model simultaneously. The gas absorption cross sections are read from external files and/or HITRAN 2004 database. The DAK model output includes all the Stokes parameters (I, Q, U, V) and fluxes at top-of-atmosphere (TOA), surface and throughout the atmosphere. In the broadband version of the DAK model, absorption coefficients of H_2O, CO_2, O_2 and O_3 are taken from databases generated by the correlated k-distribution method by Kato et al.[6]. The database of the correlated k-distribution coefficients is created from HITRAN 1992. The solar spectrum between 240 and 4600 nm has been subdivided into 32 wavelength intervals that closely follow absorption bands of the most important absorptive gases in the Earth atmosphere (see Fig. 1a).

There are four options in the DAK model considering the wavelength (λ) dependence of the aerosol/cloud optical thickness: 1) Specify the Angstrom coefficient and optical thickness at a reference wavelength (e.g. at λ_0=500 nm); the optical thicknesses at other λ's are interpolated or extrapolated. The single scattering albedo and asymmetry parameter are specified at the λ_0 only. This option is suitable for the wavelength dependence of aerosol optical thickness (AOT). 2) Specify the optical thickness and the extinction coefficient at λ_0; the optical thicknesses at other λ's are scaled with the extinction coefficients at those λ's. This option is most convenient if using Mie phase matrices, which include the scattering properties at each λ. 3) Specify the optical thickness, single scattering albedo, asymmetry parameter at every λ. The DAK model will use all the scattering properties from the input directly. Clearly this option is suitable for Henyey-Greenstein phase functions. In all the three options the optical properties can be set at any layer in the atmosphere. (4) Use LOWTRAN aerosols. Specify the AOT (at λ_0=500 nm), aerosol type, relative humidity, and visibility. The optical thickness, single scattering albedo and asymmetry parameter at other λ's are interpolated from the corresponding tabulated LOWTRAN aerosol properties.

The SMARTS model is a parameterized model based on MODTRAN, which is relatively simple compared to DAK. It is used extensively in solar energy research and various other applications. The latest version 2.9.5 is used in this comparison [5].

The intercomparison presented here consists of one case with a pure Rayleigh atmosphere and 3 cases with LOWTRAN aerosols added. For all cases, the atmospheric profile was mid-latitude summer, which includes temperature, pressure, O_3, H_2O, etc. The surface albedo was 0.1 at all wavelengths. The CO_2 mixing ratio was 370 ppmv and well-mixed. The solar spectrum was taken from the SMARTS model, called Gueymard 2003. The outputs were the direct, diffuse and total (direct + diffuse) irradiance and the irradiance spectra at SZA of 30° at the surface. The DAK model calculated the irradiances at 0, 30, 45, 60, 70, 80° SZA to save computation time, while SMARTS calculated the irradiances at SZA from 0 to 90° with 1° interval. For the aerosol cases, the AOT was 0.2 at 500 nm for all the aerosol types. We selected LOWTRAN rural, urban and maritime aerosols in the DAK model and similar Shettle and Fenn (S&F) aerosols in SMARTS. The S&F aerosol model was used in LOWTRAN, therefore the DAK and SMARTS used identical aerosol input.

MODEL COMPARISON RESULTS WITHOUT AEROSOL

The DAK and SMARTS simulated irradiance spectra are shown in Fig. 1b to check the differences at every wavelength band. The wavelength of the spectra refers to the central wavelength of the wavelength band. The irradiance spectra from SMARTS were integrated at the DAK wavelength bands because SMARTS uses finer wavelength intervals. The difference between DAK and SMARTS diffuse irradiance spectra is very small, in the worse case 0.5 W/m^2 per band. In the total irradiance spectra the largest difference was about 2 W/m^2 at 1789 and 2638 nm. The water vapor column was 2.96 cm in the DAK model and 2.92 cm in SMARTS, which could cause the irradiance to be slightly smaller in DAK, however it could not be larger than 1 W/m^2 for all the water vapor absorption bands. The SMARTS H_2O absorption coefficients are parameterized from MODTRAN, while MODTRAN absorption calculations are based on HITRAN 1992[5]. Although the correlated k-distribution used in the DAK model is also based on the HITRAN 1992, probably there are some differences in the H_2O absorption coefficients. The difference at 3318 nm might be caused by both O_3 and H_2O. The smaller differences at O_3 absorption bands (240-704 nm) are probably due to the difference in the O_3 absorption cross section and the different temperature dependence of the O_3 cross section used in the two models. Here we do not intend to check the accuracy of the absorption coefficients for SMARTS and DAK, which can only be done by line-by-line calculations. Although there are slight differences in the total irradiance spectra, the DAK and SMARTS model agree very well for the shortwave broadband irradiances, see Fig. 2. The differences of the irradiances are all less than 5 W/m^2.

MODEL COMPARISON RESULTS WITH LOWTRAN AEROSOLS

The intercomparion results for three aerosol cases are shown in Fig. 3. The direct irradiances again have good agreement between DAK and SMARTS, with a difference of 2 W/m^2. The larger differences appeared in the diffuse irradiances, especially for the urban aerosol case, although the AOT was 0.2 at 500 nm for all the aerosol cases. The difference for direct irradiances was similar at all SZA. However, the difference for diffuse irradiances decreases with increasing SZA (see Fig. 3b, d, f). The DAK model uses the original LOWTRAN aerosol properties, which are tabulated for the relative humidity (RH) between 0 and 99%. The aerosol properties are interpolated at the input relative humidity. The LOWTRAN aerosol extinction profiles are also in the DAK model. However, in SMARTS the wavelength dependence of AOT and phase function of S&F aerosol models are obtained by fitting the tabulated data in MODTRAN. Then the wavelength dependence of AOT is parameterized as a function of RH and aerosol type. The single scattering albedo is also parameterized as a function of wavelength and RH[5]. This can be the main reason for the differences in the diffuse irradiances. The direct irradiances are determined mainly by the AOT. Therefore DAK and SMARTS agree much better for the direct irradiances than for the diffuse irradiances. The rural, urban, and maritime aerosols have different parameterizations in SMARTS. Therefore it is possible that the results agree better for rural and maritime aerosol cases and worse for urban aerosol. The difference of the aerosol properties due to the parameterization may have larger impact on diffuse irradiances at larger SZA. Furthermore, the different multiple scattering approaches between DAK and SMARTS can cause the difference of diffuse irradiance at larger SZA.

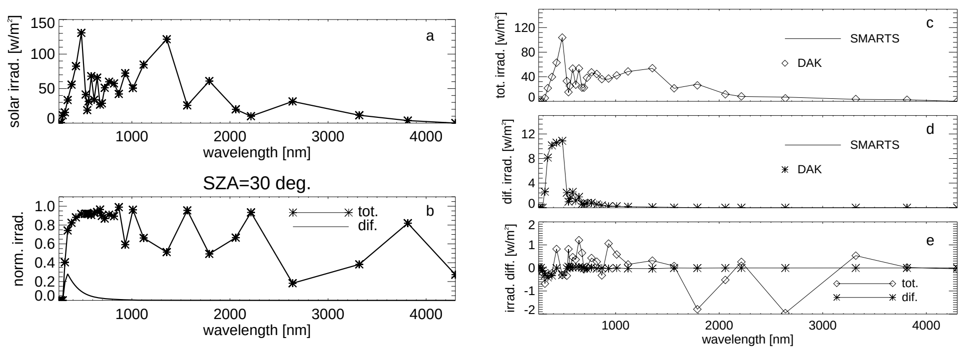

FIGURE 1. Left: (a) Solar spectrum at TOA at 32 wavelength bands. (b) DAK simulated total and diffuse irradiance spectra. The spectra are normalized. Right: DAK and SMARTS simulated (c) total irradiance spectra, (d) diffuse irradiance spectra, and (e) the differences. All the simulated spectra are at SZA= 30°.

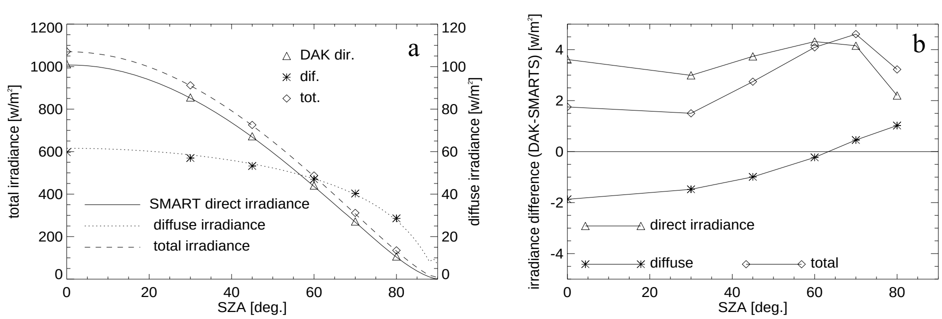

FIGURE 2. (a) DAK and SMARTS simulated direct, diffuse and total irradiances for s pure Rayleigh atmosphere. (b) The differences (DAK-SMARTS).

CONCLUSIONS

The DAK and SMARTS models are compared for clear-sky shortwave direct, diffuse and total irradiances with LOWTRAN aerosols and without aerosol. Without aerosol, DAK and SMARTS have good agreement for direct, diffuse and total irradiances with differences less than 5 W/m^2. This confirms that the correlated k-distribution has been successfully implemented in the DAK model. For the aerosol cases there is very good agreement between DAK and SMARTS for the direct irradiances; the differences are within 2 W/m^2. The diffuse irradiances have relatively larger differences for the aerosol cases, although the differences are still within 10 W/m^2. The results for the aerosol cases suggest that the single scattering albedo and asymmetry parameters are very important for the diffuse irradiances and the wavelength dependence of AOT is crucial for all irradiances. According to the comparison with the SMARTS model we believe that the DAK model can achieve similar results as other models with respect to clear-sky closure studies using BSRN (Baseline Surface Radiation Network) data. Analysis of clear-sky BSRN measurements for Cabauw, the Netherlands, using the DAK model shows excellent results.

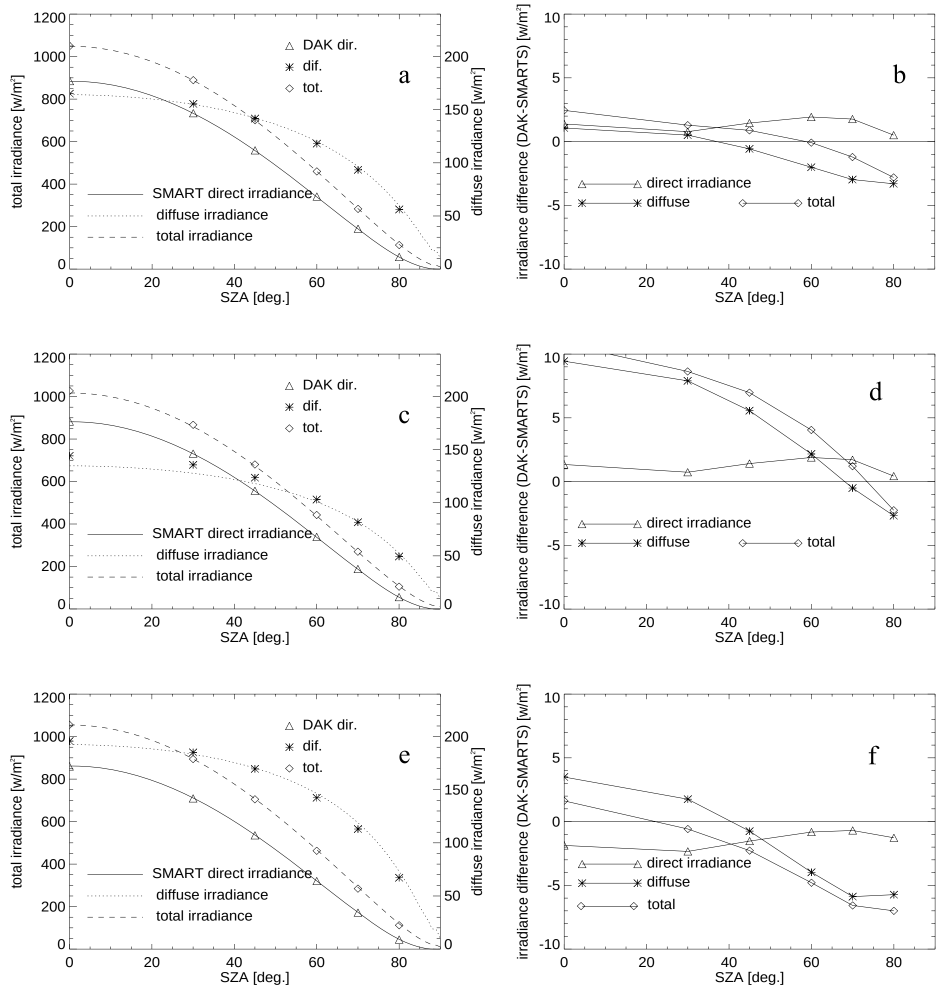

FIGURE 3. Similar as Fig. 2 but with LOWTRAN aerosols, AOT=0.2 at 500 nm.
(a, b) rural aerosol, (c,d) urban aerosol, (e,f) maritime aerosol.

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