A new approach for estimating operationally the spectral distribution of surface solar irradiance: preliminary results

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A NEW APPROACH FOR ESTIMATING OPERATIONALLY THE SPECTRAL DISTRIBUTION OF SURFACE SOLAR IRRADIANCE: PRELIMINARY RESULTS

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Abstract

The *k*-distribution method and the correlated-*k* approximation of Kato et al. (1999) are a smart approach designed for calculations of the broadband solar radiation at ground level by using only 32 spectral bands. This communication presents a preliminary assessment of the performance of this approach compared to more detailed spectral calculations for the spectral intervals no. 3 [283, 307] nm to no. 26 [1613, 1965] nm for clear and cloudy situations. For spectral intervals no. 5 [328, 363] nm to no. 26, the relative errors are less than 5% of the irradiance in the corresponding interval. The irradiance is strongly underestimated in the spectral intervals no. 3 and no. 4 [307, 328] nm. It is found that if necessary, errors may be accurately corrected with simple models computed only once.

INTRODUCTION

Surface solar irradiance (SSI) is an essential variable in many domains: climate, energy production, weather, oceanography, agriculture… There is a need for more detailed knowledge of the SSI in specific spectral bands. Examples are ultraviolet (UV) bands in relation to the cutaneous photo production of vitamin D and the human skin damages, the photosynthetically active radiation which relates to the biomass production, the daylight band of strong interest in architecture, or spectral responses of photovoltaic cells to produce electricity.

An operational approach is being studied by MINES ParisTech to estimate the irradiance in specific spectral bands. Its concept could be based on *i)* the *k*-distribution method and correlated-*k* approximation of Kato et al. (1999) which allows fast and still accurate computations, and *ii)* the decoupling concept which separates the effect of the clear atmosphere on the SSI from those due to clouds. The approximation of Kato et al. (1999) deals with the representation of the spectral distribution of the SSI in 32 discrete wavelengths intervals between 240 and 4606 nm. It is a smart approach designed for fast calculations of the broadband solar radiation at ground level by using only 32 spectral bands. The practical implication of the decoupling concept means that a model for fast calculation of SSI may be separated into two distinct and independent models, possibly abacus-based, whose input parameters and resolutions can be different, and whose creation requires less computation time and resources than a single model. The target for speed of computation is set to 10^5 times faster than accurate radiative transfer models still achieving similar accuracy.

Figure 1 exhibits the distribution of the solar spectrum of Gueymard (2004) in the 32 wavelength intervals of Kato et al. (1999) and their corresponding relative contribution to the total irradiance at top of atmosphere (TOA). These spectral intervals are noted KB in the following.

The first innovation in the operational approach studied by MINES ParisTech is the use of the *k*-distribution method and correlated-*k* approximation. This communication describes firstly the planned operational chain for estimating the spectral distribution from satellite data and outcomes from meteorological models. Then, as preliminary results, an assessment of the potentials of the 32 estimates of SSI made by the Kato et al. method is carried out in clear and cloudy skies conditions by comparison with the radiative transfer models (RTMs) libRadtran (Mayer et al., 2005) and SMARTS (Gueymard, 1995) that serve as reference in the study.

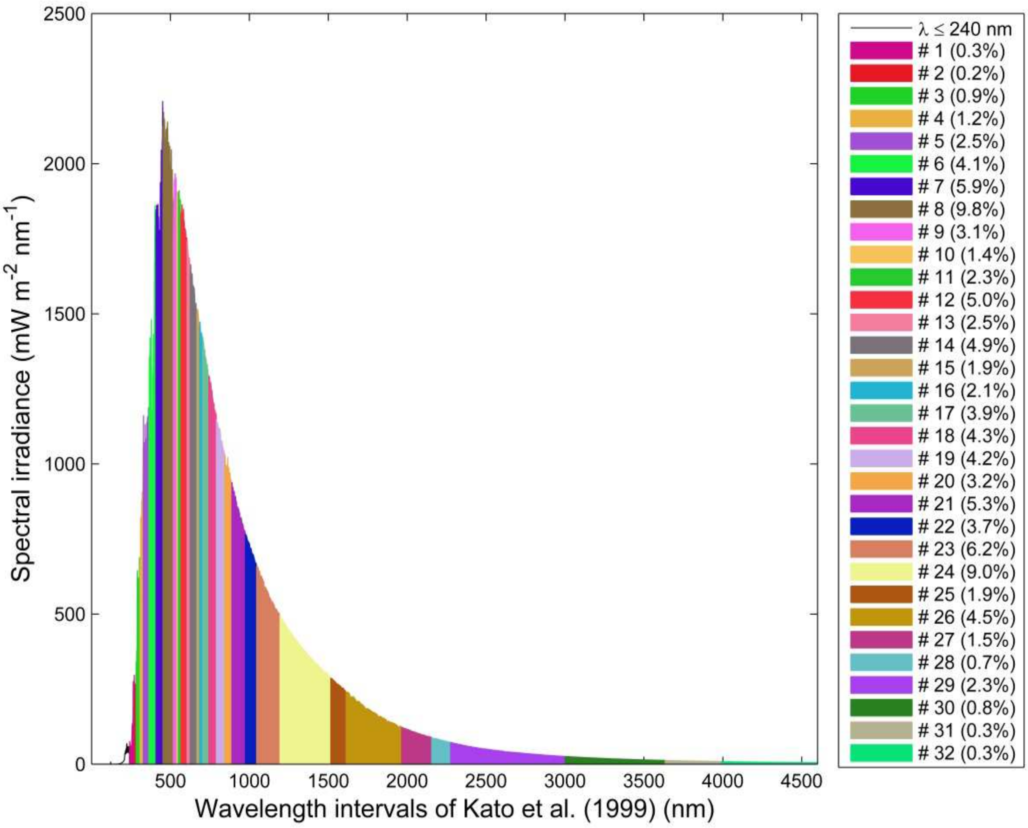

Figure 1: Distribution of the solar spectrum of Gueymard (2004) in the 32 wavelength intervals of Kato et al. (1999) and their corresponding relative contribution to the total irradiance at top of atmosphere (TOA) set to 1357.2 W m^{-2}.

OVERVIEW OF THE PLANNED OPERATIONAL CHAIN

Figure 2 exhibits a scheme of the planned operational approach. Atmospheric properties for the clear sky conditions are taken from the MACC-II project. The MACC reanalysis delivers total aerosol optical depth at 550 nm and 1240 nm from which the Angstrom coefficient and exponent are derived. Other products are the total column contents in ozone and water vapor. The clouds properties are obtained with the recent advanced products from AVHRR Processing scheme Over cLouds Land and Ocean (APOLLO) that can be obtained from DLR.

The MCD43C1 and MCD43C2 data, derived from MODIS images, are 16-day composites provided as a level-3 product of ground albedo. All of these atmospheric properties are used in the combination of Look-Up-Tables based on correlated-*k* approximation and resampling algorithm for providing the spectral distribution of solar radiation.

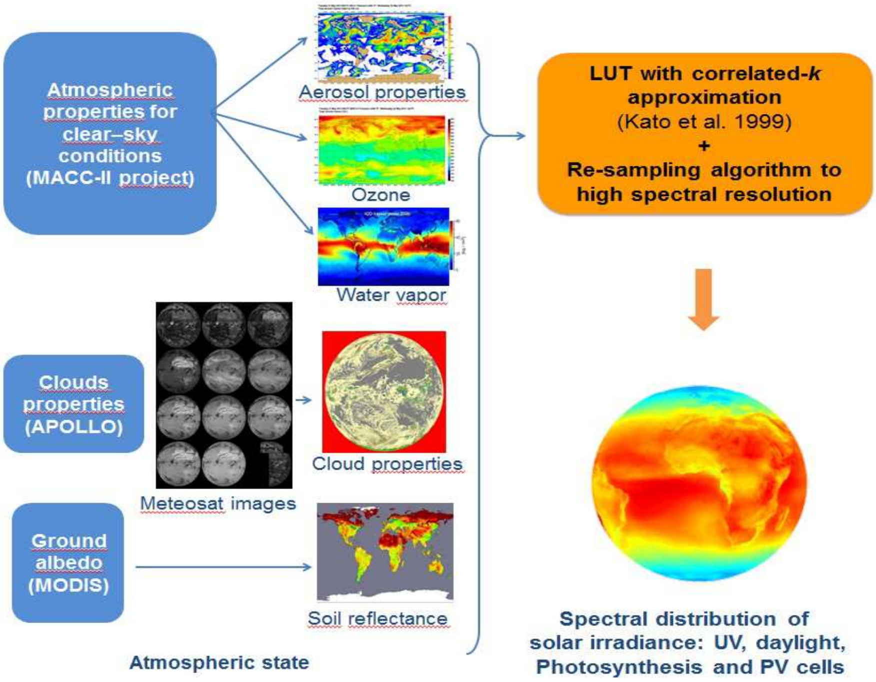

Figure 2. Overview of the planned operational chain

NUMERICAL ASSESSMENT OF THE *K*-DISTRIBUTION AND CORRELATED-*K* APPROXIMATION OF KATO ET AL. (1999)

Is the approach of Kato et al. (1999) delivering the same results than the RTMs for each KB? The method for evaluating this hypothesis is of statistical nature. Several sets of inputs to the RTMs are randomly built by a Monte-Carlo technique. Each set is input to detailed spectral calculations made by libRadtran and SMARTS, the latter being used only in clear sky conditions. The same set of inputs is also used with the correlated-*k* approximation of Kato et al. (1999) made by libRadtran (Figure 3). For each set and each KB, the differences between the estimates of the direct and global SSI made by respectively the correlated-*k* approximation and the detailed spectral calculations are computed.

The range of values taken respectively by the solar zenith angle Θs, the ground albedo ρ_g, and the variables describing the clear-sky atmosphere follows the modelled marginal distribution proposed by Lefevre et al. (2013). As for cloud properties, an approach similar to that of Oumbe et al. (2014) is followed. Ranges of cloud optical depth are related to types of clouds to produce realistic conditions and each selected cloud optical depth defines a series of triplets “cloud base, thickness” for water clouds and ice clouds.

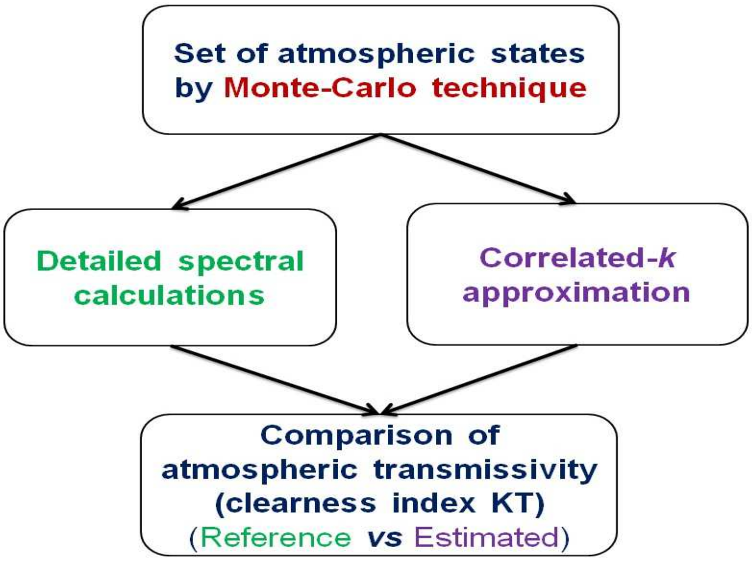

Figure 3. Procedure for the numerical validation of correlated-*k* approximation

In order to remove the daily and seasonal influence of Θs on the SSI as well as the dependency to the extraterrestrial solar spectrum, the global SSI G_i estimated by the various models in the band KB i were converted into clearness index KT_i, also called atmospheric transmissivity, atmospheric transmittance, or atmospheric transmission:

$$KT_i = \frac{G_i}{E_{o_i} cos(\Theta_s)} \qquad (1)$$

where Eo_i is the irradiance at the top of atmosphere on a plane normal to the sun rays for the band KB i. Similarly, the direct clearness index KT_i^{dir} is defined as:

$$KT_i^{dir} = \frac{B_i}{E_{o_i} cos(\Theta_s)} \qquad (2)$$

where B_i is the direct SSI.

For each set of inputs, the differences: Kato et al. estimate – detailed spectral calculation, are computed on these indices. The differences are hereafter called errors as they quantify the errors made when using the approximation of Kato et al. (1999) instead of more detailed calculation of the SSI considered as reference for each spectral interval. The errors are synthesized by the bias, the root mean square error (RMSE), the squared correlation coefficient R^2, and by the bias (rBias) and RMSE (rRMSE) relative to the mean values of KT_i^{dir} and KT_i. Relative errors are expressed relative to the mean irradiance in the corresponding KB.

RESULTS AND DISCUSSIONS

A synthesis of the relative errors in clearness index in clear-sky conditions are displayed in Fig. 4. In general, the correlation coefficient is greater than 0.99 and absolute relative error less than 5% except in the UV-band KB #3, #4 and #21. The *k*-distribution coefficients are sufficient to represent the attenuation by the atmosphere in each Kato band. Similar conclusions are obtained for the direct clearness index.

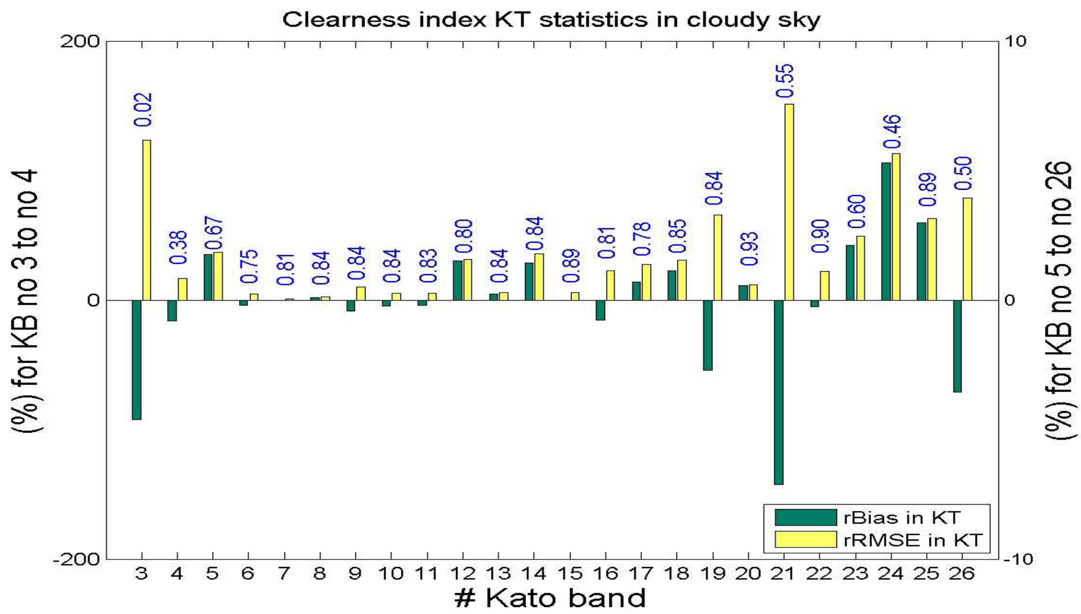

Figure 4: Synthesis of relative errors in each KB for the clearness index under clear sky conditions. Mean value of KT_i in each KB is reported in blue. Solar zenith angle less than 80°.

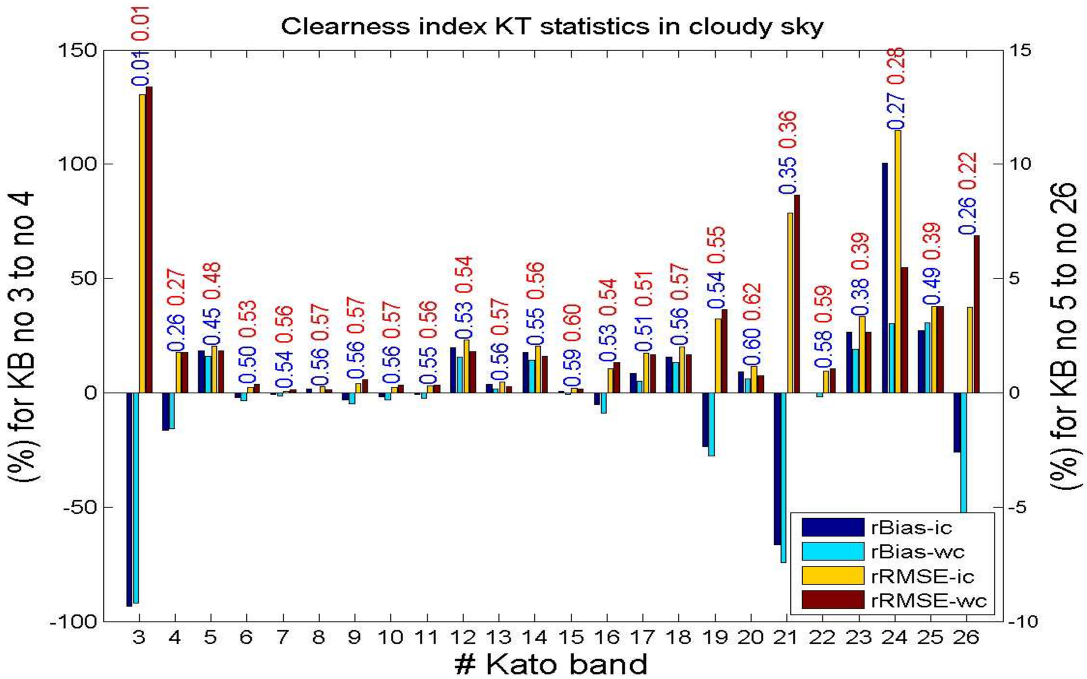

Figure 5: Synthesis of relative errors in each KB for the clearness index under cloudy conditions. Mean value of KT_i in each KB is reported in blue for ice cloud (ic) and red for water cloud (wc). Solar zenith angle less than 80°.

Similarly but for cloudy conditions, Figure 5 displays the synthesis of relative errors for the clearness index. In general, correlation coefficient is still greater than 0.99 and absolute relative error is less than 5% except in the UV-band KB #3, #4 and #21. Similar observations are made for the diret clearness index.

CONCLUSIONS

The *k*-distribution method and the correlated-*k* approximation proposed by Kato et al. (1999) for several spectral intervals offer fast and accurate estimates of the spectral irradiance in these intervals when compared to detailed spectral calculations in clear sky and cloudy conditions. In their design, these authors have evaluated the molecular scattering optical thickness, the optical properties of ozone, aerosols and clouds at the center of each interval and the obtained results demonstrate the accuracy of this approximation for most intervals. The study was limited to the bands no. 3 to 26.

For spectral intervals no. 5 [328, 363] nm to no. 26 [1613, 1965] nm, the errors are small. They amount to approximately less than 5% of the irradiance in the corresponding interval. If one expresses the errors in cloudy conditions relative to the clear sky for a medium cloud optical depth of 10, the bias and the RMSE amount to at most 0.25% of the clear sky irradiance. Said differently, the maximum error is reached for clear sky and becomes negligible as the extinction due to cloud increases. The situation is not so good for the spectral intervals no. 3 [283, 307] nm and 4 [307, 328] nm. These findings have a practical implication as they demonstrate that the errors made when using the *k*-distribution method and the correlated-*k* approximation proposed by Kato et al. (1999), though already small in most cases, may be accurately corrected with simple models such as affine functions computed only once.

These preliminary results are encouraging for further studies on how to use Kato et al. bands for estimating irradiance in specific spectral bands. A re-sampling algorithm of correlated-k results to higher spectral resolution is under development for various applications of the operational chain like the determination of illuminance, luminous efficacy, photosynthetic photon flux density, UV fluxes or short circuit density of PV devices.

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