Intercomparison of Two BRDF Models in the Estimation of the Directional Emissivity in MIR Channel From MSG1-SEVIRI Data

Geng-Ming Jiang[1, 2], and Zhao-Liang Li[1, 3,*]

[1]*Laboratoire des Sciences de l'Image, de l'Informatique et de la Télédétection, Parc d'Innovation, BP10413, 67412 Illkirch, France*
[2] *The Key Lab of Wave Scattering and Remote Sensing Information (MOE), Fudan University, 200433 Shanghai, China*
[3] *Institute of Geographic Sciences and Natural Resources Research, 100101 Beijing, China.*
[*]*Corresponding author: li@lsiit.u-strasbg.fr*

Abstract: This work intercompared two Bi-directional Reflectance Distribution Function (BRDF) models, the modified Minnaert's model and the RossThick-LiSparse-R model, in the estimation of the directional emissivity in Middle Infra-Red (MIR) channel from the data acquired by the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) onboard the first Meteosat Second Generation (MSG1). The bi-directional reflectances in SEVIRI channel 4 (3.9 μm) were estimated from the combined MIR and Thermal Infra-Red (TIR) data and then were used to estimate the directional emissivity in this channel with aid of the BRDF models. The results show that: (1) Both models can relatively well describe the non-Lambertian reflective behavior of land surfaces in SEVIRI channel 4; (2) The RossThick-LiSparse-R model is better than the modified Minnaert's model in modeling the bi-directional reflectances, and the directional emissivities modeled by the modified Minnaert's model are always lower than the ones obtained by the RossThick-LiSparse-R model with averaged emissivity differences of ~0.01 and ~0.04 over the vegetated and bare areas, respectively. The use of the RossThick-LiSparse-R model in the estimation of the directional emissivity in MIR channel is recommended.

OCIS codes: (280.0280) Remote sensing and sensors; (280.4991) Passive remote sensing; (120.3940) Metrology; (120.5630) Radiometry; (100.3190) Inverse problems.

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1. Introduction

As we know, land surface does not scatter the solar irradiance in equal quantities in all directions. In fact, it shows a behavior far from being a Lambertian reflector [1]. Bi-directional Reflectance Distribution Function (BRDF) gives the reflectance as a function of illumination geometry and view geometry. The BRDF is spectral dependent and is determined by the structural and optical properties of land surface. Many BRDF models have been developed to describe the bi-directional reflectance for operational uses, and they can be roughly classified into two categories: the purely empirical model and the semi-empirical model. For the purely empirical BRDF models, there is no physical basis for such kernels beyond their description of BRDF-like shape, such as the Minnaert’s BRDF model [2] and the Walthall’s model [3, 4]. Whereas, the semi-empirical BRDF models were derived from more complex physical theory through simplifying assumptions and approximations, such as the Roujean’s model [5], the Wanner’s model [6] and the LiSparse-Dense BRDF model [7]. Most of the BRDF models were developed over the visible and near-infrared spectrum.

The first Meteosat Second Generation (MSG1) satellite is a new generation geostationary satellite, and its main payload – the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) can provide measurements of the Earth-disc centered at (0°, 0°) every 15 min in 12 spectral channels from visible to thermal infrared at fixed view angles. Since the solar angle changes every 15 min during daytime, the MSG1-SEVIRI data are particularly suitable for the determination of the directional emissivity of land surface based on the concept of Temperature Independent Spectral Indices (TISI) [8, 9]. One of the key steps with TISI concept-based method is the estimation of the directional emissivity from the bi-directional reflectances in Middle Infra-Red (MIR) channel using a BRDF model [10].

In this work, the primary objective is to evaluate the performance of the modified Minnaert’s model used by [8, 11] against the RossThick-LiSparse-R model, in the emissivity estimation from the satellite data in SEVIRI channels 4 (3.9 μm) and 9 (10.8 μm) [12]. In the

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following, Section 2 presents the emissivity estimation using the TISI concept and the two models. Section 3 describes the study area, the data and data processing. Section 4 is devoted to the results and analysis, and the summary and conclusion are given in the last section.

2. Directional emissivity and BRDF models

For an opaque medium in thermal equilibrium, the directional emissivity $\varepsilon(\theta_v)$ is related to the hemispherical directional reflectance $\rho_h(\theta_v)$ by the Kirchhoff's law:

$$\varepsilon(\theta_v) = 1 - \rho_h(\theta_v) \tag{1}$$

where θ_v is the View Zenith Angle (VZA), and $\rho_h(\theta_v)$ is defined by [13] as

$$\rho_h(\theta_v) = \int_0^{2\pi}\int_0^{\pi/2} \rho_b(\theta_v, \theta_s, \varphi)\sin(\theta_s)\cos(\theta_s)d\theta_s d\varphi \tag{2}$$

where θ_s is the Solar Zenith Angle (SZA), φ is the Relative Azimuth Angle (RAA), and ρ_b is bi-directional reflectance of land surface.

An empirical BRDF model, the Minnaert's model, was proposed to describe the non-Lambertian reflective behavior of land surface [2], which has been widely used in planetary astronomy [14, 15]. Because the Minnaert's model does not consider the azimuth dependence, it is not sufficient to describe the directional reflectance of structured surfaces, such as forest. It was then modified by adding the RAA, and successfully applied to the emissivity estimation from the AVHRR data [10, 11]. In this work, the anisotropy factor $b(1\text{-}k^2)$ from Eq. (11) in the paper published by [11] is replaced by a unique parameter γ for convenience.

$$\rho_b(\theta_v, \theta_s, \varphi) = \rho_0[\cos(\theta_v)\cos(\theta_s)]^{k-1}[1 + \gamma\sin(\theta_v)\sin(\theta_s)\cos(\varphi)] \tag{3}$$

where ρ_0 is the reflectance with θ_v=0 and θ_s=0. k is a parameter between 0 and 1. For a Lambertian reflector, k equals to 1.

Combining Eqs. (1), (2) and (3), the directional emissivity in SEVIRI channel 4, $\varepsilon_4(\theta_v)$, is given by

$$\varepsilon_4(\theta_v) = 1 - \frac{2\pi}{k+1}\rho_0 \cos^{k-1}(\theta_v) \tag{4}$$

Different from the modified Minnaert's model, the RossThick-LiSparse-R model is a kernel-driven BRDF model, which is based on the theory that land surface reflectance typically consists of three components: the isotropic scattering, the volumetric scattering and the geometric-optical surface scattering [5]

$$\rho_b(\theta_v, \theta_s, \varphi) = k_{iso} + k_{vol} f_{vol}(\theta_v, \theta_s, \varphi) + k_{geo} f_{geo}(\theta_v, \theta_s, \varphi) \tag{5}$$

where k_{iso} is the isotropic scattering term, k_{vol} is the coefficient of the Roujean's volumetric kernel f_{vol}, and k_{geo} is the coefficient of the LiSparse-R geometric kernel f_{geo}.

The Roujean's model was developed specially for the correction of satellite data over a wide variety of surface types, and its volume kernel is a single scattering solution to the classic canopy radiative transfer equation developed by [16] for plane-parallel dense vegetation canopy with uniform leaf angle distribution, and equal leaf reflectance and transmittance. The Roujean's volumetric kernel is given by

$$f_{vol}(\theta_v, \theta_s, \varphi) = \frac{4}{3\pi}\frac{1}{\cos\theta_v + \cos\theta_s}\left[(\frac{\pi}{2} - \xi)\cos\xi + \sin\xi\right] - \frac{1}{3} \tag{6}$$

where ζ is the phase angle, related to the conventional angles by

$$\cos\xi = \cos\theta_v\cos\theta_s + \sin\theta_v\sin\theta_s\cos\varphi \tag{7}$$

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The LiSparse geometric kernel derived by [6], has been justified to work well with field measurements. This kernel is derived from the geometric-optical mutual shadowing BRDF model developed by [7], unlike the Roujean's geometrical kernel which does not consider the mutual shadowing between protrusions. The original form of this kernel is not reciprocal in θ_v and θ_s, and then was modified into a reciprocal form under the assumption that the sunlit component simply varies as $1/\cos(\theta_s)$ [17, 18], and from then the reciprocal LiSparse kernel is called LiSparse-R:

$$f_{geo} = O(\theta_v, \theta_s, \varphi) - \sec\theta_v^{'} - \sec\theta_s^{'} + \frac{1}{2}(1+\cos\xi^{'})\sec\theta_v^{'}\sec\theta_s^{'} \tag{8}$$

where

$$O(\theta_v, \theta_s, \varphi) = \frac{1}{\pi}(t - \sin t \cos t)(\sec\theta_v^{'} + \sec\theta_s^{'}) \tag{9}$$

$$\cos t = \frac{h}{b}\frac{\sqrt{D^2 + (\tan\theta_v^{'}\tan\theta_s^{'}\sin\varphi)^2}}{\sec\theta_v^{'} + \sec\theta_s^{'}} \tag{10}$$

$$D = \sqrt{\tan^2\theta_v^{'} + \tan^2\theta_s^{'} - 2\tan\theta_v^{'}\tan\theta_s^{'}\cos\varphi} \tag{11}$$

$$\cos\xi^{'} = \cos\theta_v^{'}\cos\theta_s^{'} + \sin\theta_v^{'}\sin\theta_s^{'}\cos\varphi \tag{12}$$

$$\theta_v^{'} = \tan^{-1}(\frac{b}{r}\tan\theta_v) \qquad \theta_s^{'} = \tan^{-1}(\frac{b}{r}\tan\theta_s) \tag{13}$$

where $O(\theta_v, \theta_s, \varphi)$ is the overlapping area between the view and solar shadows. The term $\cos(t)$ should be constrained to the range [-1, 1], as value outside this range imply no overlap and should be discarded. h/b and b/r are the dimensionless crown relative height and shape parameters, respectively. In MODIS BRDF/Albedo products, $h/b=2$ and $b/r=1$, which were also used in this work.

From Eqs. (1), (2) and (5), the directional emissivity in SEVIRI channel 4 is given by

$$\varepsilon_4(\theta_v) = 1 - \pi k_{iso} - k_{vol} If_{vol}(\theta_v) - k_{geo} If_{geo}(\theta_v) \tag{14}$$

with $If_x(\theta_v) = \int_0^{2\pi}\int_0^{\pi/2} f_x(\theta_v, \theta_s, \varphi)\sin(\theta_s)\cos(\theta_s)d\theta_s d\varphi$, in which the subscription x represents *vol* or *geo*.

As shown in Eq. (14), the integrals of $If_{vol}(\theta_v)$ and $If_{geo}(\theta_v)$ over the SZA and RAA are complicated mathematical expressions and can not be analytically derived. For a certain VZA ranging between 0° and 80°, the integrals were numerically calculated as shown in Fig. 1. $If_{vol}(\theta_v)$ is proportional to VZA and increases monotonously, while the opposite is observed for $If_{geo}(\theta_v)$. Several non-linear expressions with VZA as independent variable were investigated, and the Exponential Growth function (Eq. (15)) and the Gauss function (Eq. (16)) provide very good fits to $If_{vol}(\theta_v)$ and $If_{geo}(\theta_v)$, respectively

$$If_{vol}(\theta_v) = A_0 + A_1\exp(\theta_v / t_1) \tag{15}$$

$$If_{geo}(\theta_v) = B_0 + \frac{B_1}{\omega\sqrt{\pi/2}}\exp\left[-2(\frac{\theta_v - \theta_c}{\omega})^2\right] \tag{16}$$

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where A_0, A_1, t_1, B_0, B_1, θ_c and ω are unknown parameters.

The fitting results are shown in Fig. 1 and Table 1. The numerical integrals and the values predicted by the two functions with the values in Table 1 are in well agreement and nearly indistinguishable. In this work, Eqs. (15) and (16) are used instead of a look-up table.

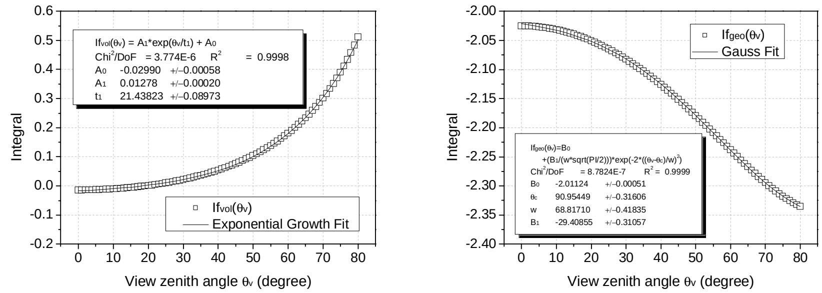

Fig. 1. Integrals and fitting results of the volumetric kernel (left) and the geometric kernel (right) of the RossThick-LiSparse-R model

Table 1. Fitting parameters of Eqs. (15) and (16)

Function	A_0 (B_0)	A_1 (B_1)	t_1 (ω) (º)	θ_c (º)
$If_{vol}(\theta_v)$	-0.02990	0.01278	21.43823	
$If_{geo}(\theta_v)$	-2.01124	-29.40855	68.81710	90.95449

The RossThick-LiSparse-R model has been widely validated with its modeling ability [19, 20, 21, 22], and has been used in the MODIS at-launch BRDF/Albedo algorithm (MODIS BRDF/Albedo Product: ATBD V5).

The inversion of the BRDF models requires bi-directional reflectances with different angular configurations, which will be estimated from the MSG1-SEVIRI data [8].

3. Study area, related data and data processing

Figure 2 shows the study area mapped onto the reference image acquired by MSG1-SEVIRI, which covers part of North Africa and Middle East. This area was selected because it contains both bare and vegetated areas according to the Global Land Cover 2000 map produced by IES (http://www-gvm.jrc.it/glc2000/). Four specific locations detailed in Table 2 are selected to demonstrate the modeling performance of the two BRDF models. Locations A, B and C are vegetated areas with different land cover types, while location D is the bare area. The VZAs of MSG1-SEVIRI at ground level at the four locations range between 39° and 52°.

The MSG Level 1.5 product, the ECMWF data, the daily averaged horizontal visibility data and the global GTOPO30 DEM data were used in this work, and two clear-sky days, July 17 and 19 of 2004 were selected. MSG Level 1.5 product is the primary data of the MSG system, derived from geometrically and radiometrically corrected level 1.0 data. The ECMWF reanalysis operational deterministic model data provide profiles of pressure, temperature, relative humidity, and geo-potential at 0.5° latitude/longitude spatial resolutions for 4 main UTC times: 0, 6, 12, 18 h (ECMWF report, 1995). The daily averaged horizontal visibility data observed at ground meteorological stations were used to indicate the amount of aerosols, and the global GTOPO30 DEM data were utilized to determine the length of the atmospheric path between surface and satellite.

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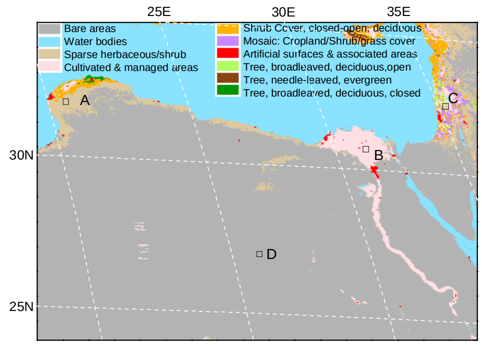

Fig. 2. Map of the study area generated from the Global Land Cover 2000

Table 2. Description of the four specific locations

No.	Longitude	Latitude	VZA* (º)	Land cover type**
A	20.583ºE	31.928ºN	45.51	Sparse herbaceous or sparse shrub cover
B	31.218ºE	30.494ºN	51.85	Cultivated and managed areas
C	35.413ºE	32.492ºN	56.33	Tree Cover, broadleaved, deciduous, open
D	25.976ºE	26.950ºN	45.40	Bare Areas

* VZA refers to the angle at ground level; ** According to the Global Land Cover 2000 map

The data in SEVIRI channel 4 and 9 over the study area in the two days were extracted from the MSG Level 1.5 product using the SEVIRI Pre-processing Toolbox (SPT), and they were then atmospherically corrected to ground level. After the atmospheric correction, the bi-directional reflectances in SEVIRI channel 4 were derived using the combined MIR and TIR data based on the TISI concept [8]. In this work, the combination of SEVIRI channels 4 and 9 was used, and the bi-directional reflectances with SZAs greater than 60° were excluded.

A Levenberg–Marquardt minimization scheme and a linear fit were applied to the inversions of Eqs. (3) and (5), respectively. If the modelling error of a measurement is greater than two times the RMSE, this measurement was removed in the next minimization or linear fit in order to discard the outlying points mainly caused by the presence of cloud in the field of view undetected by our cloud detection procedure and to stabilize the minimization procedures and consequently to get the robust estimation of the model parameters. Equation (3) is non-linear, and the initial values of the unknown parameters, which may affect the final result, were given in this way: they were firstly set to fixed values for all pixels, and then the fitting results were used as initial values in the next minimization. Finally, the directional emissivities were calculated using Eqs. (4) or (14).

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Table 3. Fitting parameters and RMSEs at the four locations on July 17 and 19 of 2004

No.	Date*	Modified Minnaert's model				RossThick-LiSparse-R model			
		ρ_0	k	γ	RMSE	k_{iso}	k_{vol}	k_{geo}	RMSE
A	July 17	0.0262	0.6083	0.2874	0.0040	0.0191	0.1647	-0.0097	0.0029
	July 19	0.0332	0.8211	0.2292	0.0038	0.0319	0.0973	-0.0032	0.0032
B	July 17	0.0089	0.6291	0.0732	0.0053	0.0026	0.0944	-0.0028	0.0030
	July 19	0.0070	0.6268	0.3327	0.0038	0.0014	0.0831	-0.0038	0.0022
C	July 17	0.0069	0.6244	0.3856	0.0040	0.0014	0.0696	-0.0032	0.0027
	July 19	0.0053	0.6615	-0.4864	0.0029	0.0022	0.0037	-0.0042	0.0027
D	July 17	0.0615	0.6894	0.0668	0.0039	0.0523	0.1871	-0.0161	0.0030
	July 19	0.0606	0.6828	0.0636	0.0041	0.0500	0.1938	-0.0173	0.0029

*All dates are in 2004.

4. Results and analysis

Table 3 gives the fitting parameters of the two models and the Root Mean Square Errors (RMSEs) at the four locations on July 17 and 19 of 2004. The fitting parameters of the two models are basically consistent in the two days, and the parameter differences between the two days may come from the minimization or linear fit: one parameter becomes larger while another one is getting smaller. All fitting RMSEs are less than 0.0054 for the two models, and the RMSEs for the RossThick-LiSparse-R model are smaller than the ones for the modified Minnaert's model. The values of the parameter K_{geo} are negative because the integrated kernel If_{geo}, as shown in Fig. 1, is always less than zero.

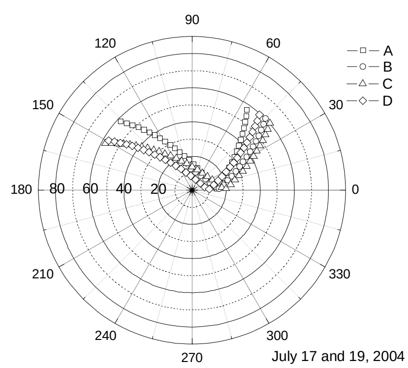

Fig. 3. Polar representation of the solar zenith angle (0º-90º) and relative azimuth angle (0º-360º) at the four locations on July 17 and 19 of 2004

Figure 3 displays the polar representation of the SZAs and RAAs at the four locations on July 17 and 19 of 2004. This illustrates that the BRDF sampling is a warping of the perpendicular plane towards the backscattering area, away from the tropical belt. The lack of the measurements in the principal plane, where the angular effects are most obvious, will lead to biased estimation of BRDF [21].

As mentioned previously, the bi-directional reflectance is a function of VZA, SZA and RAA. In order to draw them in 2-D figures, the bi-directional reflectances were normalized to a common RAA 0º for backscattering and 180º for forward scattering using Eqs. (24) and (25) for the modified Minnaert's modeled and the RossThick-LiSparse-R model, respectively

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$$\rho_{b,4}(\theta_v,\theta_s,\varphi_0)=\frac{\rho_{b,4}(\theta_v,\theta_s,\varphi)\left[1+\gamma\sin(\theta_v)\sin(\theta_s)\cos(\varphi_0)\right]}{1+\gamma\sin(\theta_v)\sin(\theta_s)\cos(\varphi)} \tag{24}$$

$$\rho_{b,4}(\theta_v,\theta_s,\varphi_0)=\frac{\rho_{b,4}(\theta_v,\theta_s,\varphi)[K_{iso}+K_{vol}f_{vol}(\theta_v,\theta_s,\varphi_0)+K_{geo}f_{geo}(\theta_v,\theta_s,\varphi_0)]}{K_{iso}+K_{vol}f_{vol}(\theta_v,\theta_s,\varphi)+K_{geo}f_{geo}(\theta_v,\theta_s,\varphi)} \tag{25}$$

Figure 4 shows the normalized bi-directional reflectances at the four locations on July 17 and 19 of 2004 at different SZA using the two models, respectively. The bi-directional reflectance changes with SZA, and the reflectances over the bare area are usually higher than the ones over the vegetated areas. The modeling results reveal that the two models can well describe the non-Lambertian reflective behavior of land surfaces, and the results in the two days are stable and consistent. Further examination shows that the RossThick-LiSparse-R model describes the bi-directional reflectances much better than the modified Minnaert's model, especially at the vegetated locations A, B and C.

Figure 5 displays the modeled bi-directional reflectances versus the estimated ones on July 17 and 19 of 2004 at the four locations using the two BRDF models. The results modeled by the modified Minnaert's model are not as well as the ones modeled by the RossThick-LiSparse-R model, and large divergences are found for those lower than 0.03, which mainly correspond to the vegetated locations A, B and C. The results modeled by the RossThick-LiSparse-R model are much better, and most of the RMSEs are less than 0.005. The mean and standard deviation of the fitting errors are, respectively, about -0.0002 and about 0.0041 for the results modeled by the modified Minnaert's model, while they are, respectively, 0.0 and about 0.0032 for the results modeled by the RossThick-LiSparse-R model.

Based on the results given in Table 3 and shown in Figs. 4 and 5, it can be concluded that the RossThick-LiSparse-R model describes the bi-directional reflectances much better than the modified Minnaert's model at both the vegetated and bare locations. The excellent performance of the RossThick-LiSparse-R model may be determined by the model itself: physics-based and linear, which is strongly different from the modified Minnaert's model in nature.

Figure 6 presents the directional emissivities in SEVIRI channel 4 modeled by the two BRDF models and the emissivity differences at the four locations on July 17 and 19 of 2004. The directional emissivities in SEVIRI channel 4 are greater than 0.87 at the vegetated locations A, B and C, while they are ~0.75 at the bare location D, which fall into the range of the results of [11]. During the two days, the directional emissivities modeled by the same model are consistent, and most of the absolute emissivity differences are less than 0.02. It is interesting to note that the directional emissivities modeled by the modified Minnaert's model are always lower than the ones modeled by the RossThick-LiSparse-R model, and the emissivity differences are about -0.015 at the vegetated locations A, B and C, while they are about -0.043 at the bare location D. From the above results, the fitting errors of the bi-directional reflectances between two models cannot lead to such large emissivity differences, therefore the emissivity differences may mainly come from the BRDF models themselves: different expression form and different model parameters. Therefore, the emissivity differences due to the BRDF models cannot be ignored, especially over the bare area.

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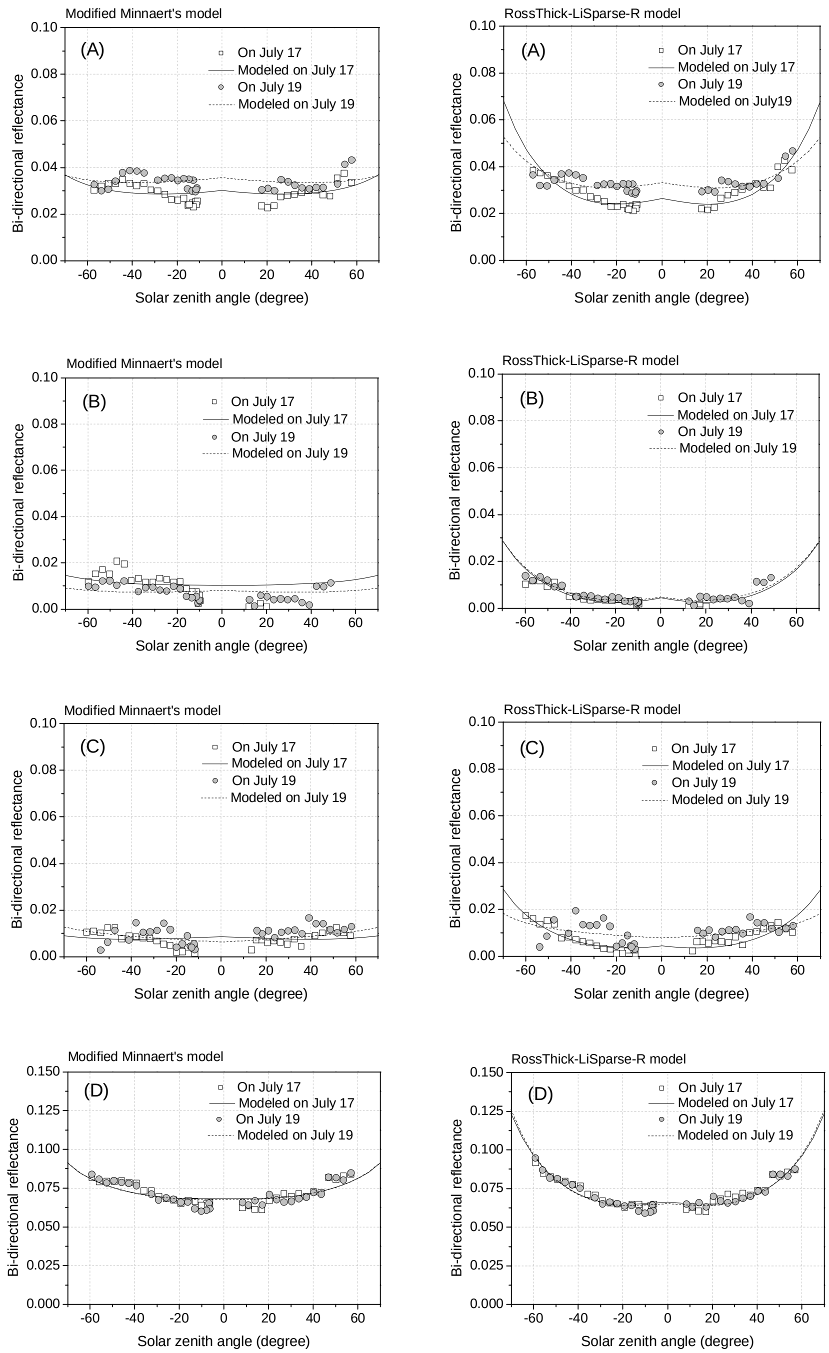

Fig. 4. Normalized bi-directional reflectance versus solar zenith angle using the modified Minnaert's model (left-hand column) and the RossThick-LiSparse-R model (right-hand column) at the four locations (φ=0° and θ_s<0 for the backscattering, while φ=180° and θ_s>0 for the forward scattering)

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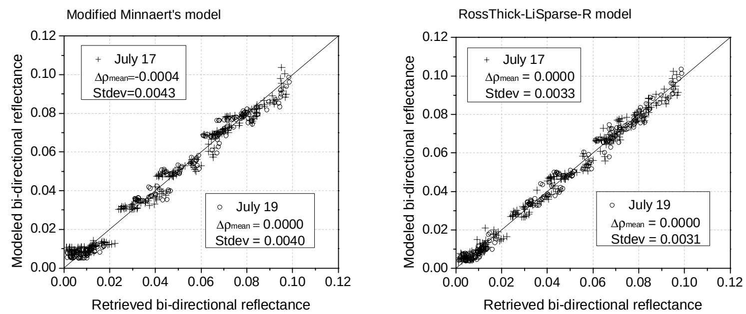

Fig. 5. Modeled bi-directional reflectances versus retrieved bi-directional reflectances on July 17 and 19 of 2004 at the four locations using the Modified Minnaert's model (left) and the RossThick-LiSparse-R model (right) ($\Delta\rho_{\mathrm{mean}}$ represents the mean of the differences between the retrieved reflectances and the modeled reflectances; Stdev is the standard deviation)

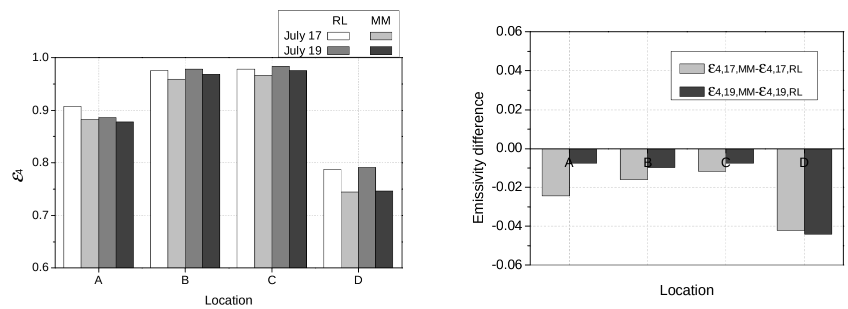

Fig. 6. Directional emissivities modeled by the two models (left) and the emissivity differences (right) (RL and MM represent for the RossThick-LiSparse-R model and the modified Minnaert's model, respectiveluy; $\varepsilon_{4,d,x}$ represents the directional emissivity in SEVIRI channel 4 on date *d* modeled by model *x*, where *x*=RL or MM)

Figure 7 demonstrates the maps of the directional emissivities in SEVIRI channel 4 modeled by the RossThick-LiSparse-R model and the emissivity differences between the two BRDF models in the two days. For the entire study area, the directional emissivities in SEVIRI channel 4 range between 0.6 and 1.0, and they are usually less than 0.85 over the bare areas, while the opposite is observed over the vegetated areas. The emissivity maps show that the directional emissivities modeled by the RossThick-LiSparse-R model in the two days are consistent and stable. The absolute emissivity differences between the two models are relatively small over the vegetated areas, while they are large over the bare areas. The mean and standard deviation of the emissivity differences are, respectively, ~-0.032 and 0.013 as given in Table 4, which means that the emissivities modeled by the modified Minnaert's model are also lower than the ones modeled by the RossThick-LiSparse-R model over the entire area.

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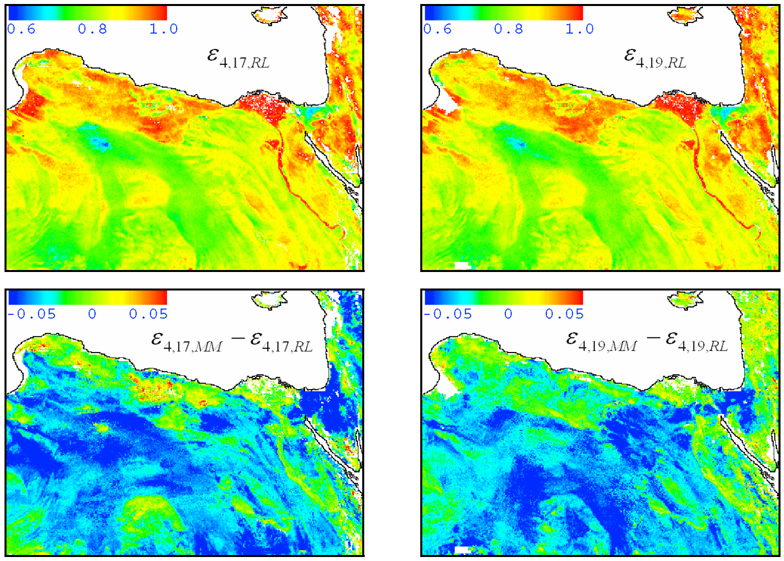

Fig. 7. Maps of the directional emissivities in SEVIRI channel 4 modeled by the RossThick-LiSparse-R model and the differences between the directional emissivities modeled by the two models on July 17 and 19 of 2004 (Variables are the same as the ones in Fig. 6)

Table 4. Averages and standard deviations of the emissivity differences over the entire study area

	$\varepsilon_{4,17,MM}$-$\varepsilon_{4,17,RL}$	$\varepsilon_{4,19,MM}$-$\varepsilon_{4,19,RL}$
Mean	-0.032	-0.033
Stdev	0.013	0.013

Variables are the same as the ones in Fig. 6.

Generally, the RossThick-LiSparse-R model describes the bi-directional reflectances much better than the modified Minnaert's model over both the vegetated and bare areas and the emissivity differences caused by the two BRDF models can not be ignored. Consequently, the use of the RossThick-LiSparse-R model in estimating the directional emissivity in SEVIRI channel 4 is recommended.

5. Summary and conclusion

This work evaluated the modeling performance of the two BRDF models, the so called modified Minnaert's model and the RossThick-LiSparse-R model, in the estimation of the directional emissivity in SEVIRI channel 4. The estimation of the directional emissivity and the two BRDF models were introduced.

An area covering part of North Africa and Middle East (Fig. 2) was selected as study area and four locations (Table 2) within this area, including both vegetated and bare areas, were used to demonstrate the modeling abilities of the two models. The MSG Level 1.5 product, the ECMWF data, the daily averaged horizontal visibility data and the global GTOPO30 DEM data on July 17 and 19 of 2004 were used. The atmospheric corrections and the estimation of the bi-directional reflectances from MSG1-SEVIRI data follow the method developed by [8]. A Levenberg-Marquardt minimization and a linear fit were, respectively, used to determine the model parameters in Eqs. (3) and (5) for each pixel, and then the emissivities in SEVIRI channel 4 were, respectively, calculated using Eqs. (4) and (14).

The modeling results by the same model in the two days are stable and consistent, and the RossThick-LiSparse-R model describes the bi-directional reflectances much better than the modified Minnaert's model over both the vegetated and bare areas; The directional emissivities modeled by the modified Minnaert's model are always lower than the ones

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modeled by the RossThick-LiSparse-R model, especially over bare areas, which mainly due to the intrinsic difference (physical vs. empirical) between the two models. In view of the modeling results, the use of the RossThick-LiSparse-R model in the estimation of the directional emissivity in MIR channel from MSG1-SEVIRI data is recommended.

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