Evaluation of land surface temperature and emissivities retrieved from MSG/SEVIRI data with MODIS land surface temperature and emissivity products

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Land surface temperature (LST) and land surface emissivity (LSE) are two key parameters in global climate study. This article aims to cross-validate LST/LSE products retrieved from data of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the first geostationary satellite, Meteosat Second Generation (MSG), with Moderate Resolution Imaging Spectroradiometer (MODIS) LST/LSE version 5 products over the Iberian Peninsula and over Egypt and the Middle East. Besides time matching, coordinate matching is another requirement of the cross-validation. An area-weighted aggregation algorithm was used to aggregate SEVIRI and MODIS LST/LSE products into the same spatial resolution. According to the quality control (QC) criterion and the view angle, the cross-validation was completed under clear-sky conditions and within a view angle difference of less than 5\textdegree for the two instruments to prevent land surface anisotropic effects. The results showed that the SEVIRI LST/LSE products are consistent with MODIS LST/LSE products and have the same trend over the two study areas during both the daytime and the night-time. The SEVIRI LST overestimates the temperature by approximately 1.0 K during the night-time and by approximately 2.0 K during the daytime compared to MODIS products over these two study areas. The SEVIRI LSE underestimates by about 0.015 in 11 \textmu m and by about 0.025 in 12 \textmu m over the Iberian Peninsula. However, both LSEs agree and show a difference of less than 0.01 over Egypt and the Middle East.

1. Introduction

Land surface temperature (LST) is one of the key parameters in the physics of land surface processes at regional and global scales. It combines the results of all surface–atmosphere interactions and energy fluxes between the atmosphere and the ground. Jiang, Li, and Nerry (2006) and Jiang and Li (2008b) developed methods to retrieve land surface emissivity (LSE) and LST from data of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the first geostationary satellite, Meteosat Second Generation (MSG-1). Because any method developed to quantitatively retrieve land surface variables and parameters from space needs to be validated, the accuracy of the LST/LSE retrieved from MSG/SEVIRI data must be assessed. Three methods are generally considered to validate LST/LSE products.
retrieved from space. The temperature-based method directly compares retrieved LST/LSE to coincident ground truth LST/LSE measurements (Wan and Li 2008). Performing field measurements is a complex and difficult task due to the difference in the size of the satellite pixels (a few square kilometres) compared to the footprint of the field sensor (a few square metres or centimetres). Moreover, natural land covers and the corresponding LST and LSE are quite variable at the scale of square kilometres. Snyder et al. (1997) pointed out that homogeneous and flat surfaces that can be easily instrumented and characterized, including inland water, sand, snow, ice, and beaches, can serve as validation sites. The size of the area that needs to be viewed by the validation instrument depends on the within-pixel variability of the surface or on how well measurements of several ‘end members’ can be mixed to obtain a representative value for the satellite pixel. This process remains challenging due to the difficulties in finding adequate surfaces in the image and performing a representative thermal sampling on the ground. The radiance-based method (Wan and Li 2008) was developed for the validation of MODIS LST products. This method does not rely on the ground-measured LST but uses surface emissivity spectra measured in the field or estimated from land-cover types and atmospheric profiles measured in the field. An iterative process is then performed using LST values from the MODIS LST product for the first round and a radiative transfer code (Moderate Resolution Atmospheric Transmission (MODTRAN) 4) to calculate the top-of-atmosphere (TOA) radiance values in MODIS band 31 (L31). MOD L31 inverted LSTs can be obtained by adjusting the LST input values of MODTRAN 4 in the simulations to match the calculated L31 values with the MODIS-measured radiance (MOD L31) values. This last value is compared to the MODIS LST product, and the result shows that differences are usually within 1 K for lake, vegetation, and soil sites in clear-sky conditions. The LST difference may be slightly larger for bare soil and highly heterogeneous sites because of large uncertainties in surface emissivities. Unlike the temperature-based method, LSE measurements or estimations are required. The cross-validation method uses an LST product as a reference. The inter-comparison between LST products estimated from different satellites has been complemented (Cristina et al. 2005; Noyes et al. 2006; Jiang 2007; Trigo et al. 2008). However, the view angle difference of different satellites was not considered in these cases.

In this article, we focus on the cross-validation of LST/LSE derived from MSG/SEVIRI data (Jiang, Li, and Nerry 2006; Jiang and Li 2008b) with LST/LSE extracted from MOD11B1 and MOD11_L2 products, which were considered here as references, under clear-sky conditions. Section 2 recalls the retrieval method of LST/LSE from MSG/SEVIRI data and describes the products of MODIS LST/LSE (MOD11B1 and MOD11_L2) and the study areas. Section 3 presents the cross-validation procedure. Section 4 is devoted to the results and analysis. The last section gives the summary and conclusion.

2. Descriptions of LST/LSE retrieval method from MSG/SEVIRI of MODIS LST/LST products and study areas

2.1. MSG/SEVIRI LST and LSE retrievals

MSG/SEVIRI is a 12-channel imager with a 15 minute repeat cycle and a 3 km at-nadir spatial sampling distance. The high-resolution visible channel has a 1 km spatial sampling distance (Schmetz et al. 2002). Four channels are in the infrared atmospheric windows and three of them (centre wavelengths at 3.9, 10.8, and 12.0 µm) will allow the estimation of LST and LSE.
LST is estimated using the generalized split-window algorithm that expresses LST as a linear function of the brightness temperatures measured by SEVIRI at TOA in atmospheric window channels centred at 10.8 and 12.0 \( \mu m \):

\[
LST = \left( A_1 + A_2 \frac{1 - \varepsilon}{\varepsilon} + A_3 \frac{\Delta \varepsilon}{\varepsilon} \right) \frac{T_{10.8} + T_{12.0}}{2} + \left( B_1 + B_2 \frac{1 - \varepsilon}{\varepsilon} + B_3 \frac{\Delta \varepsilon}{\varepsilon} \right) \frac{T_{10.8} - T_{12.0}}{2} + C,
\]

where the parameters \( A_1, A_2, A_3, B_1, B_2, B_3, \) and \( C \) are constants for a given class of emissivity, atmospheric column water vapour (\( W \)), and sub-range of LST. The mean surface emissivity and emissivity difference of the 10.8 and 12.0 \( \mu m \) channels are \( \varepsilon \) and \( \Delta \varepsilon \), respectively. The TOA brightness temperature at the 10.8 and 12.0 \( \mu m \) channels are \( T_{10.8} \) and \( T_{12.0} \), respectively.

Coefficients \( A_1, A_2, \ldots, C \) of the split-window algorithm were proposed by Jiang and Li (2008b). The generalized split-window algorithm was developed for eight view zenith angles (VZAs) by dividing the LST, average emissivity (\( \varepsilon \)), and column water vapour (\( W \)) into several sub-ranges to improve LST-estimated accuracy.

Jiang, Li, and Nerry (2006) proposed a method to estimate LSE by combining the mid-infrared (MIR) and thermal infrared (TIR) data of MSG/SEVIRI. A new atmospheric correction scheme was developed for both MIR and TIR data. Because the MIR channel is less sensitive to the water vapour content change, the closest temporary atmospheric profile from the European Centre for Median-Range Weather Forecast (ECMWF) was used. A diurnal temperature cycle (DTC) model (Göttsche and Olesen 2001) with six unknown parameters was used to perform the atmospheric correction for the TIR channels. The LSE in the MIR channel was retrieved based on the concept of the temperature-independent spectral indices (TISIs) (Becker and Li 1990) and with the kernel-driven RossThick-LiSparse-R model (Wanner, Li, and Strahler 1995; Jiang and Li 2008a). The LSEs of the TIR channels were retrieved using TISI and LSE in the MIR channel.

2.2. MODIS LST and LSE products

The MODIS (Terra and Aqua) LST products (MOD11_L2 and MOD11B1) have been validated with \textit{in situ} measurements in more than 50 clear-sky cases in the temperature range from –10 to 58°C and the column water vapour range from 0.4 to 4 cm (Wan et al. 2002, 2004; Coll et al. 2005; Wan 2006, 2007; Wan and Li 2008). Taking into account the higher accuracies within 1 K for both Terra and Aqua LST products, only the Terra LST product is used for the validation data.

The MODIS/Terra MOD11_L2 V5 product is an LST product at 1 km spatial resolution and is produced using the generalized split-window LST algorithm. The corresponding latitude and longitude data are stored in the MODIS geolocation product (MOD03). The emissivities of bands 31 and 32 are estimated by the classification-based emissivity method (Snyder et al. 1998), according to the land-cover types.

The MODIS/Terra MOD11B1 V5 product, tile-based and gridded in the sinusoidal projection at a 6 km spatial resolution, is produced by the day/night LST algorithm (Wan and Li, 1997) from pairs of daytime and night-time observations in the seven MODIS TIR bands (bands 20, 22, 23, 29, 31, 32, and 33). For most situations, this method yields accuracies of 1 K for LST and 0.01 for LSE in channels 31 and 32. The MOD11B1 product also contains the QC file for LST/LSE. The VZA and the solar zenith angle (SZA) are stored in the MOD11_L2 and MOD11B1 products. These parameters are needed for data processing and cross-validation in this study.
2.3. Study areas

Two regions were selected as study areas for the LST/LSE cross-validation. One area is the Iberian Peninsula area, covering Spain and Portugal (longitude: 12.87° W–4.15° E; latitude: 35.86° N–44.98° N) (Figure 1(a)), and the other is Egypt and the Middle East (longitude: 27.65° E–37.59° E; latitude: 27.53° N–35.82° N) (Figure 1(b)). The Iberian Peninsula area is a vegetated region, and the main land-cover types are cultivated and managed areas, tree cover, and herbaceous cover. Egypt and the Middle East are dominated by bare surfaces. Most of Egypt is covered by the low-lying sand dunes and depressions of the Western and Libyan deserts. These two study areas, with typical land-cover types, are suitable for LST/LSE cross-validation.

The MODIS/Terra MOD11_L2 LST/LSE products of the Iberian Peninsula and Egypt and the Middle East were downloaded according to the acquisition time of the MODIS/Terra orbit tracks (http://www.ssec.wisc.edu/datacenter/terra/). The MODIS/Terra MOD11B1 LST/LSE product is a composite of data from several neighbouring orbits at different daily acquisition times. The Iberian Peninsula can be covered with tiles h17v04 and h17v05, and Egypt and the Middle East can be covered with tiles h20v05, h20v06, h21v05, and h21v06 according to the MOD11B1 sinusoidal grid (http://nsidc.org/data/modis/data_summaries/landgrid_v5.html).

3. Cross-validation procedure

3.1. Aggregation method of LST and LSE

Coordinate matching is a key factor for cross-validation. The SEVIRI LST/LSE and MOD11B1 or MOD11_L2 products must be aggregated to the same spatial resolution of SEVIRI using the area-weighted pixel aggregation algorithm. The SEVIRI and MOD11B1 or MOD11_L2 data are accurately matched with the minimum root mean square error (RMSE) principle. An area-weighted algorithm (see Equation (2)) is employed in this work:

\[
L_R = \sum_{r=1}^{N} \omega_r L_r \left/ \sum_{r=1}^{N} \omega_r \right. = A_{r,R} / A_r,
\]
where \( L_R \) is the aggregated radiance of the target pixel \( R \); \( L_r \) is the radiance of pixel \( r \); \( N \) is the total number of pixels within the aggregated pixel \( R \); \( \omega_r \) is the weight of pixel \( r \) within the aggregated pixel \( R \); \( A_{r,R} \) is the partial area of pixel \( r \) that falls within the target (aggregated) pixel \( R \); and \( A_r \) is the total area of pixel \( r \). An analogous equation is used to aggregate emissivity. The coordinates derived from the product generally represent the central location of one pixel. The coordinates of the four corners of a pixel are easily calculated using the coordinates of the neighbouring pixels. Based on the spatial relationship, the weights \( \omega_r \) of the small pixels \( (1, \ldots, N) \) are calculated using the polygon intersection algorithm and the aggregated value of the large pixel \( R \) is obtained.

3.2. Spectral relationship between MODIS and SEVIRI emissivities

The spectral relationship of emissivity between the TIR channels of SEVIRI and MODIS should be considered in order to compare the LSE between MODIS and SEVIRI data. The spectral response functions of the MSG/SEVIRI and MODIS Terra instruments are presented in Figure 2.

The spectral emissivities, including water, ice, snow, vegetation, soil, and minerals, are extracted from the MODIS University of California, Santa Barbara (UCSB) emissivity library (http://www.ices.ucsb.edu/modis/EMIS/html/em.html) to account for the spectral differences in the TIR channels between SEVIRI and MODIS. The channel emissivities in the SEVIRI and MODIS TIR channels were calculated, and the linear relationships between the MODIS and SEVIRI channel emissivities were determined by linear fitting (Figure 3):

\[
\begin{align*}
\epsilon_{31} &= 0.9492 \times \epsilon_9 + 0.04916, \\
\epsilon_{32} &= 0.9279 \times \epsilon_{10} + 0.02757,
\end{align*}
\]

where \( \epsilon_9 \) and \( \epsilon_{10} \) are the emissivities of SEVIRI channels 9 and 10, respectively. The emissivities of MODIS channels 31 and 32 are \( \epsilon_{31} \) and \( \epsilon_{32} \), respectively. The fitting correlation coefficients are greater than 0.99 and the standard deviations are less than 0.0015. Comparison of emissivity between the MODIS and SEVIRI channels is performed only after the emissivities in SEVIRI channels 9 and 10 are transformed to the emissivities in MODIS channels 31 and 32 using Equation (3).

Figure 2. MSG/SEVIRI and MODIS/Terra spectral response functions.
3.3. Data processing

To carry out the cross-validation, the LSTs/LSEs derived from the MSG/SEVIRI data using the generalized split-window algorithm and extracted from the MODIS/Terra MOD11_L2 and MOD11B1 products over the Iberian Peninsula and over Egypt and the Middle East were aggregated to the same spatial resolution using Equation (2). In this work, the MOD11_L2 product (1 km) is aggregated to the spatial resolution of the SEVIRI LST product (3 km). Furthermore, the SEVIRI LST product is aggregated to the spatial resolution of the MOD11B1 product (6 km).

Besides coordinate matching, time matching is another requirement for LST/LSE cross-validation. This cross-validation can be completed with a high accuracy only if the view time is accurately determined. The MOD11B1 product is a composite of several neighbouring orbits with a difference in acquisition time of about 90 minutes according to the tracks of the Terra’s orbit. The view times (local time) stored in MOD11B1 are divided into 12 minute-wide strips. The UTC time as a function of the longitude of each pixel can be calculated. The UTC acquisition time of the MOD11_L2 product can be directly determined from the MOD11_L2 file name. Because the SEVIRI sensor provides an image every 15 minutes and the nearest SEVIRI acquisition time to MODIS acquisition time is used to evaluate the SEVIRI LST product, the maximum difference of the acquisition time between these two products is 7.5 minutes.

VZA is the third key parameter for cross-validation. SEVIRI VZAs vary from 43° to 50° over the Iberian Peninsula and from 45° to 55° over Egypt and the Middle East. Only pixels with a view angle difference between the two instruments smaller than 5° (an arbitrary number) are used for cross-validation to prevent land surface anisotropic effects and to minimize the effect of the different view angles on the determination of LST/LSE. Because the Iberian Peninsula area is covered mainly by vegetation and Egypt and the Middle East are covered mainly by sand, they are relatively homogeneous and are considered to have isotropic behaviour. Consequently, LST should not be greatly affected by the relative azimuth angle (RAA), which is not considered in this article.

According to the QC criterion of the MODIS product, the MODIS product will provide good data quality and will be cloud-free when QC is equal to zero, where both the average emissivity errors in MODIS channels 31 and 32 are less than 0.01 and the average LST error is less than 1.0 K in the MOD11B1/MOD11_L2 product. Thus, only the pixels of the MODIS product with a value of zero in QC flags are used for cross-validation. Figure 4 shows the flowchart for the cross-validation.
4. Results and analysis

Data of the given nine days – 14–19 July 2004, 14 July 2005, 1 July 2006, and 9 September 2006 – covering the years 2004, 2005, and 2006 were used in the LST/LSE cross-validation. These data sets were selected since few or no clouds were present over the study areas. About 120,000 points between the SEVIRI and MOD11B1/MOD11L2 products met the above conditions and were used for cross-validation for these days.

Figure 5 shows the daily mean and RMSE of differences between SEVIRI LST and MODIS/Terra LST over the Iberian Peninsula and over Egypt and the Middle East. If no matching pixels are available according to the view angle and QC files, no comparison results are shown in Figures 5 and 6. Table 1 lists the acquisition dates and numbers of pixels that met the above conditions and were used for cross-validation. The mean and RMSE of the temperature differences at daytime are larger than those at night-time over the two study areas (Figure 5). The mean LST difference is about 2 K during the daytime and about 1 K at night-time.

Table 2 gives the average LST difference and the RMSE for all days over the two study areas. Compared with MOD11B1 and MOD11_L2 LST, the mean of the SEVIRI LST difference has a similar value over the Iberian Peninsula during the daytime. However, over Egypt and the Middle East, the LST comparison result between the SEVIRI LST and the MOD11_L2 LST is better than that between the SEVIRI LST and the MOD11B1 LST during the daytime. The SEVIRI LST over the two study areas are within 1.0 K compared
Figure 5. Daily mean and RMSE of temperature differences between the SEVIRI LST ($T_{\text{SEVIRI}}$) and MOD11B1 and MOD11_L2 LST ($T_{\text{MODIS}}$) products. The deviation bars are centred on the mean of the temperature (denoted by the points), and the half-length of the bar is equal to the RMSE of the temperature difference. The left two figures are daytime LST difference, and the right two figures are night-time LST difference. The numbers 1–9 on the $x$-axis denote the dates of 14–19 July 2004 (1–6), 14 July 2005 (7), 1 July 2006 (8), and 19 September 2006 (9).
Figure 6. Daily mean and RMSE of emissivity differences between SEVIRI LSE and MOD11B1 and MOD11_L2 LSE products. The deviation bars are centred on the mean of the emissivity (denoted by the points), and the half-length of the bar is equal to the RMSE of the emissivity difference. The two figures on the left and right correspond to the LSE difference at 11 and 12 µm over the vegetated Iberian Peninsula, respectively. The numbers 1–9 on the x-axis denote the dates of 14–19 July 2004 (1–6), 14 July 2005 (7), 1 July 2006 (8), and 19 September 2006 (9).

large. The largest emissivity differences occurred on 19 September 2006, with mean and RMSE of 0.034 and 0.037 at 11 µm, and 0.047 and 0.050 at 12 µm, respectively. (Table 3). The number of SEVIRI LSEs retrieved over the entire Iberian Peninsula on 19 September 2006 is small. This is because the Iberian Peninsula was covered by long-time clouds on this day, which affected the retrieval of the SEVIRI LSEs based on the multi-temporal satellite data.

Table 3 shows the mean LSE for all days over the two study areas. The SEVIRI LSEs at 11 and 12 µm for all days over the Iberian Peninsula are ~0.015 and ~0.025 lower than the MOD11B1 and MOD11_L2 LSE products. The SEVIRI LSEs at 11 and 12 µm for all days over Egypt and the Middle East are ~0.01 lower than the MOD11B1 and MOD11_L2 LSE products. The two comparison results are the same.

Using the two MODIS LSE products (MOD11B1 and MOD11_L2) to validate the SEVIRI LSE, the comparison results at 11 and 12 µm are very similar. This similarity can lead to the conclusion that the same results will be obtained using the MOD11B1 or MOD11_L2 LSE product to validate the SEVIRI LSE (Figure 6 and Table 3). However, the LSE comparison results in both TIR channels over Egypt and the Middle East are better than those over the Iberian Peninsula. The reason for the large LSE difference between the SEVIRI and MODIS products might be the fact that the retrieved SEVIRI LSE is based on the time series satellite data in a day and the Iberian Peninsula area was covered by many more clouds for a longer period than Egypt and the Middle East. However, the retrieved MODIS LSEs are based on the classification-based emissivity method or the day/night LST
Table 1. Acquisition dates and numbers of pixels used for comparison.

<table>
<thead>
<tr>
<th>Study area</th>
<th>Date</th>
<th>Number of pixels used for LSE comparison</th>
<th>Number of pixels used for LST comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MOD11B1</td>
<td>MOD11_L2</td>
<td>MOD11B1</td>
</tr>
<tr>
<td>Iberian Peninsula</td>
<td>14 July 2004</td>
<td>163</td>
<td>1096</td>
</tr>
<tr>
<td></td>
<td>15 July 2004</td>
<td>1158</td>
<td>2214</td>
</tr>
<tr>
<td></td>
<td>16 July 2004</td>
<td>0</td>
<td>159</td>
</tr>
<tr>
<td></td>
<td>17 July 2004</td>
<td>768</td>
<td>1941</td>
</tr>
<tr>
<td></td>
<td>18 July 2004</td>
<td>428</td>
<td>1136</td>
</tr>
<tr>
<td></td>
<td>19 July 2004</td>
<td>1350</td>
<td>5062</td>
</tr>
<tr>
<td></td>
<td>14 July 2005</td>
<td>721</td>
<td>3460</td>
</tr>
<tr>
<td></td>
<td>1 July 2006</td>
<td>66</td>
<td>604</td>
</tr>
<tr>
<td></td>
<td>19 September 2006</td>
<td>253</td>
<td>1804</td>
</tr>
<tr>
<td>Egypt and the Middle East</td>
<td>14 July 2004</td>
<td>1713</td>
<td>7166</td>
</tr>
<tr>
<td></td>
<td>15 July 2004</td>
<td>1657</td>
<td>4430</td>
</tr>
<tr>
<td></td>
<td>16 July 2004</td>
<td>2424</td>
<td>8265</td>
</tr>
<tr>
<td></td>
<td>17 July 2004</td>
<td>1845</td>
<td>4482</td>
</tr>
<tr>
<td></td>
<td>18 July 2004</td>
<td>5940</td>
<td>10,512</td>
</tr>
<tr>
<td></td>
<td>19 July 2004</td>
<td>1382</td>
<td>6121</td>
</tr>
<tr>
<td></td>
<td>14 July 2005</td>
<td>2118</td>
<td>11,190</td>
</tr>
<tr>
<td></td>
<td>1 July 2006</td>
<td>2803</td>
<td>11,145</td>
</tr>
<tr>
<td></td>
<td>19 September 2006</td>
<td>3798</td>
<td>11,585</td>
</tr>
</tbody>
</table>

algorithm. Thus, in spite of MODIS LSEs being of a high quality and being obtained under clear-sky conditions, the differences of LSEs between the SEVIRI and MODIS products might have great discrepancies. The low spatial resolution of the ECMWF atmospheric profiles used for the atmospheric correction in the SEVIRI TIR channels might affect the accuracy of the atmospheric correction. Meanwhile, the reflectance in the retrieved MIR channel depends on the assumption that the downwelling radiance does not vary for several hours and can be obtained from the ECMWF data, which will influence the retrieval accuracies of the reflectance and emissivity in the MIR channel.
Table 2. Mean LST differences for all days.

<table>
<thead>
<tr>
<th>Study area</th>
<th>Definition of $\Delta T$</th>
<th>Acquisition time</th>
<th>Number of pixels</th>
<th>Mean RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iberian Peninsula</td>
<td>$T_s - T_{s,MOD11B1}$</td>
<td>Day</td>
<td>2688</td>
<td>2.50 3.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Night</td>
<td>2219</td>
<td>0.50 1.53</td>
</tr>
<tr>
<td></td>
<td>$T_s - T_{s,MOD11_L2}$</td>
<td>Day</td>
<td>8568</td>
<td>2.12 3.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Night</td>
<td>8908</td>
<td>0.69 1.94</td>
</tr>
<tr>
<td>Egypt and the Middle East</td>
<td>$T_s - T_{s,MOD11B1}$</td>
<td>Day</td>
<td>15536</td>
<td>2.20 3.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Night</td>
<td>8144</td>
<td>0.73 1.86</td>
</tr>
<tr>
<td></td>
<td>$T_s - T_{s,MOD11_L2}$</td>
<td>Day</td>
<td>37216</td>
<td>1.23 2.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Night</td>
<td>36340</td>
<td>0.70 1.96</td>
</tr>
</tbody>
</table>

Note: $T_s$ is the temperature retrieved from MSG/SEVIRI data; $T_{s,MOD11B1}$ is the temperature of the MOD11B1 product; and $T_{s,MOD11_L2}$ is the temperature using the MOD11_L2 product.

Table 3. Mean LSE differences for all days.

<table>
<thead>
<tr>
<th>Study area</th>
<th>MODIS product</th>
<th>Number of pixels</th>
<th>$\varepsilon_9 - \varepsilon_{31}$ Mean RMSE</th>
<th>$\varepsilon_{10} - \varepsilon_{32}$ Mean RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iberian Peninsula</td>
<td>MOD11B1</td>
<td>4907</td>
<td>-0.016 0.022</td>
<td>-0.026 0.031</td>
</tr>
<tr>
<td></td>
<td>MOD11_L2</td>
<td>17,476</td>
<td>-0.015 0.023</td>
<td>-0.025 0.031</td>
</tr>
<tr>
<td>Egypt and the Middle East</td>
<td>MOD11B1</td>
<td>23,680</td>
<td>-0.009 0.016</td>
<td>-0.009 0.018</td>
</tr>
<tr>
<td></td>
<td>MOD11_L2</td>
<td>73,556</td>
<td>-0.009 0.017</td>
<td>-0.010 0.020</td>
</tr>
</tbody>
</table>

Notes: $\varepsilon_9$ and $\varepsilon_{10}$ are the transformed emissivity using Equation (3) against MSG/SEVIRI emissivities in channels 9 and 10, respectively. $\varepsilon_{31}$ and $\varepsilon_{32}$ are MODIS emissivities in channels 31 and 32, respectively.

5. Conclusions

LST retrieved from satellite data can be validated using temperature-based, radiance-based, or cross-validation methods in coincidence with a satellite overpass. In this article, the cross-validation method is used to validate the retrieved SEVIRI LST/LSE according to the MODIS LST/LSE products over the Iberian Peninsula and over Egypt and the Middle East.

According to the MOD11B1 and MOD11_L2 products to validate the SEVIRI LST/LSE, similar validation results can be obtained during the daytime or night-time over the two study areas. The mean SEVIRI LSTs are $\sim$2.0 and $\sim$1.0 K larger than those of the MOD11B1 and MOD11_L2 products during the daytime and night-time, respectively. The larger LST differences over the Iberian Peninsula are probably caused by the larger differences in retrieved LSE. However, the relatively large RMSE of LST differences during the daytime in all cases are somewhat concerning. The comparison results of LST at night-time are better than those during the daytime because the surface temperature at night-time is more homogeneous.

Compared to the LSEs extracted from MOD11B1 and MOD11_L2, the SEVIRI LSEs at 11 and 12 $\mu$m underestimate the emissivities by about $\sim$0.015 and $\sim$0.025 over the Iberian Peninsula and by about $\sim$0.01 and $\sim$0.01 over Egypt and the Middle East. The large differences in LSE for the Iberian Peninsula might be attributed to more clouds and to the low spatial resolution of the ECMWF atmospheric profiles used for the atmospheric
correction in the SEVIRI TIR channels. This needs to be investigated further. Although the retrieved SEVIRI LST error is within 1 K using simulated data, the large SEVIRI view angle over the two study areas also impacts the retrieval accuracy of the SEVIRI LST from satellite data (Jiang, Li, and Nerry 2006). The best match is achieved between the SEVIRI LST/LSE and the MOD11_L2 LST/LSE over Egypt and the Middle East (Tables 2 and 3).

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