**Quality assessment and validation of the MODIS global land surface temperature**

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**Abstract.** This paper presents an evaluation of the Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) thermal infrared bands and the status of land surface temperature (LST) version-3 standard products retrieved from Terra MODIS data. The accuracy of daily MODIS LST products has been validated in more than 20 clear-sky cases with *in situ* measurement data collected in field campaigns in 2000–2002. The MODIS LST accuracy is better than 1°C in the range from −10 to 50°C. Refinements and improvements were made to the new version of MODIS LST product generation executive code. Using both Terra and Aqua MODIS data for LST retrieval improves the quality of the LST product and the diurnal feature in the product due to better temporal, spatial and angular coverage of clear-sky observations.

1. **Introduction**

As a part of the NASA-centred international Earth Observing System, two MODIS instruments (Salomonson et al. 1989) have been launched to provide information for global studies of atmosphere, land, and ocean processes. The first was launched on 18 December 1999 on the morning platform called Terra, and the second was launched on 4 May 2002 on the afternoon platform called Aqua. The Terra overpass time is around 10:30am (local solar time) in its descending mode and 10:30pm in ascending mode. The Aqua overpass time is around 1:30pm in ascending mode and 1:30am in descending mode. The strengths of the MODIS instrument include its global coverage, high radiometric resolution and dynamic ranges, and accurate calibration in visible, near-infrared and thermal infrared bands. The Terra MODIS data have been used to generate science data products for more than two years and these science data products are available to the public free of charge. A consistent reprocessing has been made for Terra MODIS data since November 1999 to generate science data products (version 3) in either...
provisional quality or validated quality. Science data products based on Aqua MODIS data will also be available after the testing and evaluation stage.

LST is one of the key parameters in the physics of land surface processes on regional and global scales. It combines the results of all surface–atmosphere interactions and energy fluxes between the atmosphere and the ground (Mannstein 1987, Sellers et al. 1988). The LST retrieved from satellite data may be used to validate and improve the global meteorological model prediction after appropriate aggregation and parameterization (Price 1982, Diak and Whipple 1993). The remotely sensed LST has been used in land cover and land cover change analysis (Ehrlich and Lambin 1996, Lambin and Ehrlich 1997), and in the production of the MODIS land cover product. It has been also used in monitoring drought and estimating surface soil moisture (Feldhake et al. 1996, McVicar and Jupp 1998), evaluating water requirements of wheat (Jackson et al. 1977), and determining frosts in orange groves (Caselles and Sobrino 1989).

In the following sections, we present an evaluation of the MODIS thermal infrared (TIR) bands used for LST retrieval, a brief summary of the MODIS LST algorithms, validation status of the MODIS LST product, new refinements and improvements made to the operational LST code (version 4), and the major advantages of using Terra and Aqua MODIS data for the LST product.

2. Performance of MODIS TIR bands

The specification and estimated performance of the TIR bands in the MODIS Proto-Flight Model (PFM) flown on Terra are shown in table 1. The channel-dependent noise and systematic error in MODIS TIR channel data were evaluated with early MODIS data over lake and ocean sites in clear sky days acquired with the A-side of scan mirror and electronics before the end of October 2000 (Wan 2002). In 14 cases of sub-area sites with a size of 10 lines by 16 pixels, where the

<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth (μm)</th>
<th>IFOV specified (km)</th>
<th>IFOV estimated (km)</th>
<th>NEDT specified (km)</th>
<th>NEDT (K) estimated (Wan, 2002)</th>
<th>Calibration bias estimated (K) (before 31 October 2000)</th>
<th>Calibration bias estimated (K) (after 3 July 2001)</th>
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<tbody>
<tr>
<td>20</td>
<td>3.660–3.840</td>
<td>1</td>
<td>0.05</td>
<td>0.06</td>
<td>0.60</td>
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<tr>
<td>21</td>
<td>3.929–3.989</td>
<td>1</td>
<td>2.00</td>
<td>0.64</td>
<td>0.46</td>
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<tr>
<td>22</td>
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<td>1</td>
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<td>0.07</td>
<td>0.55</td>
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<td>23</td>
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<td>1</td>
<td>0.07</td>
<td>0.05</td>
<td>0.40</td>
<td>−0.08</td>
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<tr>
<td>24</td>
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<td>0.13</td>
<td></td>
<td></td>
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<tr>
<td>25</td>
<td>4.482–4.549</td>
<td>1</td>
<td>0.25</td>
<td>0.08</td>
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</tr>
<tr>
<td>27</td>
<td>6.535–6.895</td>
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<td>0.25</td>
<td>0.12</td>
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<tr>
<td>28</td>
<td>7.175–7.475</td>
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<td>0.09</td>
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<tr>
<td>29</td>
<td>8.400–8.700</td>
<td>1</td>
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<td>31</td>
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<td>1</td>
<td>0.05</td>
<td>0.03</td>
<td>0.12</td>
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<tr>
<td>32</td>
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<td>−0.19</td>
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<tr>
<td>33</td>
<td>13.185–13.485</td>
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<td>0.25</td>
<td>0.16</td>
<td>0.55</td>
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<tr>
<td>34</td>
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<td>0.25</td>
<td>0.27</td>
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<td></td>
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<tr>
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<td>13.785–14.085</td>
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<td>0.25</td>
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<td></td>
<td></td>
<td></td>
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<td>14.085–14.385</td>
<td>1</td>
<td>0.35</td>
<td>0.41</td>
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brightness temperature in band 31 changes within $\pm 0.1$ K, average and standard deviation values of brightness temperatures in 10 channels (as a 10-element linear detector array) of 16 MODIS TIR bands show the channel-dependent noise and systematic errors. It is found that the specification of noise equivalent temperature difference (NEDT) is reached or nearly reached in all but three channels (the ninth in bands 21 and 24, and the fourth in band 22) of the 16 MODIS TIR bands as shown in column 5 of table 1.

The absolute radiometric accuracy of MODIS TIR channel data was evaluated with in situ data collected in a vicarious calibration field campaign conducted in Lake Titicaca, Bolivia, during 26 May and 17 June 2000 (Wan et al. 2002a). The comparison between MODIS TIR data produced by the version 2.5.4 Level-1B code and the band radiances calculated with atmospheric radiative transfer code MODTRAN4.0 (Berk et al. 1999) based on lake surface temperatures measured by five IR radiometers deployed in the high-elevation Lake Titicaca, and the atmospheric temperature and water vapour profiles measured by radiosondes launched on the lake-shore on calm clear-sky days of 13 and 15 June 2000, shows good agreements in bands 29, 31 and 32 (within an accuracy of 0.5%) in daytime overpass cases. Sensitivity analysis indicates that the changes in the measured atmospheric temperature and water vapour profiles result in negligible or small effects on the calculated radiances in bands 20–23, 29, and 31–32. Therefore, comparisons for these bands were made for cases when lake surface temperature measurements were available but no radiosonde data were available, and in sub-areas of 10 by 16 pixels where there was no in situ measurement, but MODIS brightness temperatures in band 31 varied within $\pm 0.15$ K by using the validated band 31 to determine lake surface temperatures. These comparisons show that the specified absolute radiometric accuracy of 1% is reached or nearly reached in MODIS bands 21, 29 and 31–33, and that there is a calibration bias of 2–3% in bands 20, 22, and 23, as shown in column 6 of table 1.

The MODIS sensor was reconfigured on 31 October and 1 November 2000 to the B-side Science Mode from the A-side Science Mode. By transiting to latest focal plane bias voltage in the B-side configuration, the three originally noisy detector elements returned to normal performance. The MODIS instrument experienced a Power Supply 2 shutdown anomaly and did not take science data during the time period of 15 June to 2 July 2001. The MODIS instrument was reconfigured to the A-side Science Mode with the same focal plane bias voltage used in the B-side mode on 3 July 2001. The MODIS data in this configuration are referred to as new A-side data. To evaluate the calibration accuracy of the new A-side data, we conducted a field campaign in Walker Lake, Nevada in mid October 2001. The estimated calibration bias is less than 1% in bands 22–23, 29, and 31–32, as shown in column 7 of table 1 (Wan et al. 2002b). Note that the uncertainty in the estimate in band 33 is larger due to the uncertainty in atmospheric condition.

The relative spectral response (RSR) functions of Terra and Aqua MODIS instruments in bands 20, 22, 23, 29 and 31–33 are shown in figure 1. The effects of the difference between Terra and Aqua MODIS RSR functions are less than 0.1K in these seven bands.

We use the Terra and Aqua MODIS data over Lake Titicaca on 26 June 2002 to estimate the NEDT of the early Aqua MODIS TIR bands. Their granule IDs are MOD021KM.A2002177.0300 and MYD021KM.A2002177.0600. A sub-area with a size of 10 lines by 16 pixels was searched for the smallest variations in the brightness temperatures in band 31 within the lake in these two granules. The standard
deviation values in brightness temperatures are used to estimate the NEDT. The 
comparison of the estimated NEDT values between Terra and Aqua MODIS TIR 
bands shown in figure 2 indicate that the quality of Aqua MODIS data is better in 
most TIR bands.

Figure 1. Terra and Aqua MODIS relative spectral response functions.
3. MODIS LST algorithms

3.1. Basic considerations

LST is retrieved from MODIS TIR data only in clear-sky conditions so that LST is not mixed with cloud-top temperature. Because TIR signals cannot penetrate clouds and the probability of cloudy conditions is often larger than 50% at the regional and global scales, cloudy pixels must be skipped in the LST processing.

LST is defined by the radiation emitted by the land surface observed by MODIS at instant viewing angles. The land surface here means canopy in vegetated areas or soil surface in bare areas. Instant MODIS TIR data collected at one viewing angle do not contain information at other viewing angles due to weak scattering of the TIR signals in the clear-sky atmosphere. We recognize that applications may need LST at different angles (nadir in some cases or 50° in other cases). Referring LST at other angles from the value at a given viewing angle is a research topic that requires detailed information of the surface proportions and structures, which is not available at the global scale.

Appropriate resolution of the land–atmosphere coupling is the key in retrieving surface and atmospheric properties. Although advances have been made in integrated retrieval (Ma et al. 2000, 2002), this approach is very time consuming computationally. It is not practical to implement the integrated retrieval of the surface and atmospheric properties at a spatial resolution of several kilometers as operational at this time. Instead, we use multiple bands in the atmospheric windows for the LST retrieval. The values of atmospheric temperature and water vapour are useful to improve LST retrieval. However, there may be large errors in these values. Therefore, we use them only as indicators of ranges or initial guess values.
3.2. The generalized split-window LST algorithm

The LST of clear-sky pixels in MODIS scenes is retrieved from brightness temperatures in bands 31 and 32 with the generalized split-window algorithm (Wan and Dozier 1996). The coefficients used in the split window algorithm are given by interpolation on a set of multi-dimensional look-up tables (LUT). The LUTs were obtained by linear regression of the MODIS simulation data from radiative transfer calculations over wide ranges of surface and atmospheric conditions. Improvements for the generalized split-window LST algorithm incorporated in the establishment of the LUTs include: (1) view-angle dependence, (2) column water vapour dependence, and (3) dependence on the atmospheric lower boundary temperature.

The band emissivities, also called classification-based emissivities (Snyder et al. 1998) are estimated from land cover types in each MODIS pixel through a LUT based on TIR BRDF and emissivity modelling (Snyder and Wan 1998). A simple linear correction is made to the band emissivities to account for the viewing angle effect in the emissivities when the viewing angle is larger than 45 degrees for some land cover types. In the at-launch MODIS LST processing, the University of Maryland IGBP-type land-cover based on AVHRR data (Townshend et al. 1994) is used to provide global land cover information at 1 km grids. Since June 2001, the MODIS land-cover product (Muchoney et al. 1999) is used in the MODIS LST processing. Note that errors and uncertainties in the classification-based emissivities may be large in semi-arid and arid regions because of the large temporal and spatial variations in surface emissivities and lack of knowledge on the emissivity variation with viewing angle.

3.3. The MODIS day/night LST algorithm

A physics-based day/night algorithm (Wan and Li 1997) was developed to retrieve surface spectral emissivity and temperature at 5 km resolution from a pair of daytime and nighttime MODIS data in seven TIR bands, i.e. bands 20, 22, 23, 29, and 31–33. To our knowledge, this day/night algorithm is the first operational LST algorithm capable of adjusting the uncertainties in atmospheric temperature and water vapour profiles for a better retrieval of the surface emissivity and temperature without a complicated complete simultaneous retrieval of surface variables and atmospheric profiles. Because we use a pair of daytime and nighttime MODIS data in seven bands, we have 14 observations. In the day/night algorithm, there may be a maximum of 14 unknown variables. The minimal set of the surface variables includes seven band emissivities, and daytime and nighttime surface temperatures. Because of the close coupling between land surface and atmosphere, uncertainties in surface emissivities may result in large errors in the atmospheric temperature/water vapour retrieval (Plokhenko and Menzel 2000). These errors could exist in the shape of the retrieved temperature/humidity profile, and in the values of atmospheric temperature at the surface level (\(T_a\)) and column water vapour (cwv). Atmospheric radiative transfer simulations show that the MODIS radiances in the above seven TIR bands are relatively less sensitive to changes in the shapes of temperature and water vapour profiles. Therefore, we set four atmospheric variables (\(T_a\) and cwv, for daytime and nighttime, respectively). Then there is only one unknown left for the anisotropic factor of the solar beam BRDF at the surface. Bidirectional reflectance measurements of sands and soils (Snyder et al. 1997) show that although there are quite strong spectral variations in surface reflectance for most terrestrial materials in the 3.5–4.2 \(\mu\)m wavelength range,
their BRDF anisotropic factor in this wavelength range has very small variations, in the order of 2%. Therefore, we can use a single anisotropic factor for bands 20, 22, and 23. The set of 14 nonlinear equations in the day/night algorithm is solved with the least-squares fit method (Wan and Li 1997).

Considering the angular variation in surface emissivity, we separate the whole range of MODIS viewing zenith angles into sub-ranges, and use one emissivity in each of the sub-ranges. In the day/night LST processing, we select a pair of clear-sky daytime and night MODIS observations at view angles in a same sub-range whenever it is possible. If there is no such pair of day/night observations available in a reasonable short period of time but there is a pair of day/night observations in different sub-ranges of view angle, we use this less favorable pair for surface emissivity and temperature retrieval and set a lower quality for the retrieved results. In the version-3 product generation executive (PGE) code, the whole range of MODIS viewing zenith angle is separated into four sub-ranges (0°–40°, 40°–52°, 52°–60° and 60°–65°).

4. Status of the MODIS LST product

The level-2 MODIS LST product (MOD11_L2) in version 3, available from EDC DAAC (http://edcdaac.usgs.gov/modis/dataprod.html), is retrieved with the generalized split-window algorithm (Wan and Dozier 1996) in the product generation executive (PGE) LST code from the calibrated radiance data of bands 31 and 32 data in the MODIS Level-1B 1km resolution (MOD021KM) product.

The daily 1 km resolution level-3 MOD11A1 LST product is constructed with the results in the MOD11_L2 products of a day through mapping the science data sets of all pixels in the MOD11_L2 products onto grids in the integerized sinusoidal projection and averaging the values in each grid.

The physics-based day/night algorithm (Wan and Li 1997) was used to retrieve surface spectral emissivity and temperature at 5 km resolution for the MODIS LST level-3 MOD11B1 product from a pair of daytime and nighttime MODIS data in TIR bands 20, 22, 23, 29, and 31–33.


The accuracy of daily MODIS LST product at 1 km resolution generated by the generalized split window algorithm was validated in 11 clear-sky cases with in situ measurement data collected in field campaigns in 2000 and 2001 (Wan et al. 2002b). The MODIS LST accuracy is better than 1K in the range from 263 K to 300 K over Lake Titicaca in Bolivia, Mono Lake, Bridgeport grassland, and a rice field in Chico, California, and Walker Lake, Nevada, in the atmospheric column water vapour range from 0.4 to 3.0 cm. In six cases over a silt playa in Railroad Valley, Nevada, the 1 km MODIS LSTs are a few Kelvin degrees lower than the in situ measured LSTs because the surface emissivities inferred from land cover types in the split-window LST method are often overestimated in semi-arid and arid regions. After a correction with the difference between the 5 km LST retrieved by the day/night LST method and the LST aggregated from 1 km LSTs retrieved by the split-window method, the MODIS LSTs agreed with in situ measured LSTs within ±1K in the range from 263 K to 322 K for the six cases in Railroad Valley and one case of snow cover in Bridgeport, California.
Table 2. Comparison between the MODIS LSTs and *in situ* measured LSTs in validation field campaigns conducted in a soybean field (33.08263° N, 90.7866° W), Mississippi, in 2002. The atmospheric column water vapour (cwv) comes from the atmospheric MOD07_L2 product, $\delta T_s$ stands for the standard deviation in the LST values at four pixels neighboring the averaged position of IR radiometers.

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Granule ID</th>
<th>Date and time</th>
<th>View zenith (°)</th>
<th>Atmos. cwv (cm)</th>
<th>In situ $T_s$ from radiometers (K)</th>
<th>MODIS $T_s$ ($\delta T_s$) (K)</th>
<th>MODIS – <em>in situ</em> $T_s$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A2002199.0415</td>
<td>17 July 23:16 CDT</td>
<td>6.99</td>
<td>3.5</td>
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</tr>
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<td>2</td>
<td>A2002215.0415</td>
<td>2 August 23:16 CDT</td>
<td>6.62</td>
<td>3.3</td>
<td>298.3</td>
<td>298.3 (0.17)</td>
<td>0.0</td>
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<tr>
<td>3</td>
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<td>4 August 23:04 CDT</td>
<td>18.17</td>
<td>3.0</td>
<td>297.6</td>
<td>297.2 (0.20)</td>
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<tr>
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<td>38.85</td>
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<td>294.5</td>
<td>293.6 (0.30)</td>
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<td>5</td>
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<td>18.68</td>
<td>3.3</td>
<td>295.7</td>
<td>295.5 (0.28)</td>
<td>−0.2</td>
</tr>
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</table>
In order to validate the LST product in wet atmospheric conditions, we conducted field campaigns in the low Mississippi River basin late in June–August 2002. Five radiometers were deployed in a soybean field, and three in a rice field at Greenville, Mississippi. These radiometers are the same type of IR radiometers used in our vicarious calibration and LST validation field campaigns (Wan et al. 2002a, 2002b). The same procedures to correct the effects of surface emissivity and reflectance are used in the data processing. The accuracy of the radiometers is better than 0.2 K. The validation results in five clear-sky nights are given in table 2. The daytime in situ measurement data are not used because of large spatial variations in the in situ data. Note that a part of the larger difference between the LST and in situ values at viewing zenith angle near 40° may be due to the uncertainty in estimated surface emissivities. We will measure the LST at multiple angles in the future field campaigns.

In summary, the version-3 MODIS LST products were validated at multiple sites in relatively wide ranges of surface and atmospheric conditions. More ground-based measurements will be made to validate the LST products, especially for the products retrieved from Aqua MODIS data.

5. Improvements of the MODIS LST Product Generation Executive (PGE)

The following new refinements and improvements were made to the version-4 MODIS LST PGE code: (1) update of the look-up tables (LUT) used in the day/night LST algorithm; (2) processing of lake pixels in clear-sky at a confidence of 66% and higher; (3) use of BRDF/Albedo parameters of the MODIS 16-day BRDF product (MOD43B1C) as input; (4) separation of the range of viewing zenith angles into five sub-ranges (0–24°, 24–38°, 38–49°, 49–58°, and 58–65°) instead of four; (5) parallel processing of data in odd and even days to double the production rate and the storage of interim results for the day/night algorithm; (6) incorporation of a split-window method into the day/night algorithm to ensure that the retrieved emissivities can be used by split-window algorithms.

In a new option added to the MODIS LST PGE code, if the BRDF parameters for band 7 (at 2.13 µm) in MOD43B1C in the previous 16-day period are available, they will be used to provide a better initial value for the anisotropic factor of the solar beam BRDF at the surface in the day/night LST algorithm. This anisotropic factor is used for bands 20, 22, and 23 (in the spectral region of 3.6–4.1 µm). Although the reflectance values in these two spectral regions may be different for terrestrial materials, they vary in similar ranges (Salisbury et al. 1991). Because BRDF parameters depend on the surface materials and structure, there should be a strong correlation between the BRDF parameters in these two spectral regions. With this new option, the knowledge of the BRDF parameters in the short wave TIR spectral region (in band 7 at 2.13 µm) is used to provide a better initial value of the anisotropic factor to the solution of the day/night LST algorithm. Because of the non-linearity of the day/night LST algorithm, a better initial value will lead to a better solution of the algorithm, giving more accurate surface emissivities and temperatures.

The MODIS LST PGE code is also modified to add an option to use both Terra and Aqua MODIS data in the day/night LST algorithm for better solutions of the surface emissivities and temperatures. By a combined use of Terra and Aqua MODIS data, the chance of clear-sky observations will be roughly doubled, and the chance to have a pair of daytime and nighttime observations at viewing angles in
the same sub-ranges will be significantly increased so that the accuracy of the retrieved surface emissivities can be improved.

In the version 4 reprocessing started in the end of 2002, the accuracies of retrieved

Figure 3. Spatial distribution of the LST diurnal variation in the regions of Europe, North Africa and the Middle East. The images are the LSTs around 10:30am (upper left), 1:30pm (upper right), 10:30pm (lower left), and 1:30am (lower right).

Figure 4. Colour composite images of the retrieved surface emissivities (a) with bands 29, 22, and 20 as RGB components, (b) with bands 29, 31, and 32 enhanced by the equalization histogram method as RGB components.
LST and surface emissivities will also be improved due to the improvements in the qualities of input MODIS products including calibrated radiance, atmospheric temperature/water vapour profile, cloud mask, land cover and snow cover.

Terra and Aqua MODIS data collected in the early Aqua mission (25–26 June and 4–9 July 2002) have been processed at the science computing facility of the UCSB MODIS LST group with the refined PGE code. In figure 3, the retrieved daytime and nighttime LSTs averaged in this period of time show spatial

Figure 5.  (a) Comparison between retrieved surface emissivities over the Sahara Desert and those measured from sand samples in the laboratory. (b) Comparison between retrieved surface emissivities in Caspian Sea and the theoretical emissivity values of the sea water.
distribution of the LST diurnal variation in the regions of Europe, North Africa, and Middle East. The retrieved surface emissivities are shown in figure 4 in colour composite image with emissivities in bands 29, 22, and 20 as RGB components (figure 4(a)), and the one with emissivities in bands 29, 31, and 32 enhanced by the equalization histogram method as RGB components (figure 4(b)). The comparison between retrieved surface emissivities over the Sahara Desert and those measured from sand samples in the laboratory is shown in figure 5(a). Three of the sand samples were brought from stores and another one was collected from the beach near UCSB. The comparison between retrieved surface emissivities in Caspian Sea and the theoretical emissivity values of the sea water is shown in figure 5(b). It is interesting to mention that there are correlations among the spatial distributions of retrieved emissivities (figure 4) and those of surface reflectances in visible and near infrared bands, and vegetation index (not shown) in the related MODIS products.

6. Conclusions

The MODIS LST products have been validated within 1K in multiple validation sites in relatively wide ranges of surface and atmospheric conditions. Refinements and updates were made to improve the quality of the LST product and to use both Terra and Aqua MODIS data in the LST retrieval. The major advantages of the additional Aqua MODIS data for the LST product include the increase in quantity and the improvement in quality of the surface emissivity and temperature science data over the global land due to the increasing number of MODIS observations in clear-sky conditions. With the MODIS observations four times a day for nearly every spot on the Earth and more frequently in high latitude regions, the diurnal variation feature will be kept in the LST product. Because of the Aqua overpass time around 1:30pm, the afternoon LSTs retrieved from the MODIS data will be more close to the maximum temperature of the land surface so that it is more suitable for regional and global change studies, especially in applications for estimating soil moisture condition and water requirements of crops, and for monitoring drought.

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References


