Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 112 (2008) 623–635
Remote Sensing of Environment
www.elsevier.com/locate/rse

Validating MODIS land surface temperature products using long-term nighttime ground measurements

Wenhui Wang [a,*], Shunlin Liang [a], Tilden Meyers [b]

[a] Department of Geography, University of Maryland, United States
[b] Atmospheric Turbulence and Diffusion Division, NOAA, United States

Received 29 August 2006; received in revised form 27 April 2007; accepted 19 May 2007

Abstract

The Moderate Resolution Imaging Spectroradiometer (MODIS), onboard the NASA Terra and Aqua Earth Observing System satellites, provides multiple land surface temperature (LST) products on a daily basis. However, these products have not been adequately validated. This paper presents preliminary results of validating two MODIS Terra daily LST products, MOD11_L2 (version 4) and MOD07_L2 (version 4), using the FLUXNET and Carbon Europe Integrated Project (CarboEurope-IP) long-term ground measurements over eight vegetated sites. Since ground-measured LSTs were only available over one fixed point in each validation site, the study was carefully designed to mitigate the scale mismatch issue by using nighttime ground measurements concurrent to more than 1800 MODIS Terra overpasses.

The preliminary results show that MOD11_L2 LSTs have smaller absolute biases and root mean squared errors (RMSE) than those of MOD07_L2 LSTs in most cases. The match of MOD11_L2 LSTs with ground measurements in the Brookings, Audubon, Canaan Valley, and Black Hills sites is good, yielding absolute biases less than 0.8 °C and RMSEs less than 1.7 °C. In the Fort Peck, Hainich, Tharandt, and Bondville sites, MOD11_L2 LSTs were underestimated by 2–3 °C. Biases in MOD11_L2 LSTs correlate to those in MOD07_L2 LSTs. Since the MOD07_L2 LST product is one of the input parameters to the MOD11_L2 LST algorithm, biases in MOD11_L2 LSTs may be influenced by biases in MOD07_L2 LSTs. The errors in both products depend weakly on sensor view zenith angle but are independent of surface air temperature, humidity, wind speed, and soil moisture.

Keywords: Land surface temperature; MODIS; Validation; FLUXNET; CarboEurope-IP

1. Introduction

Land surface temperature (LST) is a key variable in climatological and environmental studies (Liang, 2001; Peres & DaCamara, 2004; Pinheiro et al., 2004; Wan, 1999; Wan & Dozier, 1996; Wan & Li, 1997a,b). Multiple daily LST products (on a global scale) are generated by the science team of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the NASA Terra and Aqua Earth Observation System satellites. Table 1 lists the product name, spatial resolution, stated accuracy, and algorithm principle of the Terra MODIS daily LST products. These products are referred to as MOD11_L2, MOD11A1, MOD11B1, and MOD07_L2 in the rest of the paper. MOD11_L2 is retrieved using a generalized split-window algorithm by MODIS land team (Wan, 1999; Wan & Dozier, 1996). MOD11A1 is a gridded version of MOD11_L2, generated by projecting MOD11_L2 pixels to Earth locations on a sinusoidal mapping grid. MOD11B1, another LST product from the MODIS land team, is retrieved using a day/night algorithm (Wan, 1999; Wan & Li, 1997a,b). MOD07_L2 LST is produced using a statistical regression-based method by the MODIS atmosphere team (Seemann et al., 2003). Similar products are available from MODIS Aqua observations.

Meteorological, hydrological, and agricultural research communities require an accuracy of 0.5–2 °C for LST retrieved from satellite observations at 1–10 km spatial resolution (CEOS & WMO, 2000; GCOS, 2006). MODIS LST products have been validated in previous studies (Coll et al., 2005; Menzel et al., 2002; Wan et al., 2004a,b, 2002). The accuracy of MOD11_L2 and MOD11B1 LST products is reported to be 1 °C for the surfaces with known emissivity (Wan et al., 2002). However, the reported accuracy cannot be applied to the

* Corresponding author. Tel.: +1 301 4054538.
E-mail address: whwang1@umd.edu (W. Wang).

0034-4257/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2007.05.024

Table 1
Summary of Terra MODIS daily LST products

Product short name	Product full name	Stated accuracy (°C)	Spatial resolution (km)	Algorithm principle	References
MOD11_L2	Land surface temperature/emissivity daily 5-min L2 swath 1 km	1	1	Generalized split-window algorithm; statistical-based	Wan and Dozier (1996), Wan (1999)
MOD11A1	Land surface temperature/emissivity daily L3 global 1 km SIN grid	1	1	Reprojected from MOD11_L2 to a sinusoidal mapping grid	Wan and Dozier (1996), Wan (1999)
MOD11B1	Land surface temperature/emissivity daily L3 global 5km SIN grid	1	5	Day/night algorithm; physics-based	Wan and Li (1997a,b), Wan (1999)
MOD07_L2	Temperature and water vapor profiles 5-min L2 swath 5 km	N/A	5	Statistical regression	Menzel et al. (2002), Seemann et al. (2003)

MOD11_L2 and MOD11B1 products in their entirety, because land surface emissivity is usually unknown and retrieving it on a global scale is as challenging as LST retrieval. For vegetated sites, MOD11_L2 and MOD11B1 performances were validated using only limited ground measurements during the growing season. The MOD07_L2 LST product has been evaluated indirectly using ground measurements from the Southern Great Plains Atmospheric Radiation Measurement Cloud and Radiation Testbeds (SGP ARM-CART) site.

MODIS LST products have been used in various studies (Mostovoy et al., 2006; Nagler et al., 2005; Sun et al., 2005; Tran, 2006; Wan et al., 2004a,b; Wang et al., 2006, 2005). However, the errors caused by LST were mostly disregarded in these studies. While MODIS LSTs provide a potentially inexpensive means to validate and improve existing land surface and climate models, MODIS LST products have often been ignored by the modeling community until recently. The major concern is that the accuracy of these LST products has not been adequately assessed. To facilitate the use of MODIS LST products for broader application, more validation work is required.

The purpose of this study is to assess the accuracy of two MODIS LST products, MOD11_L2 LST and MOD07_L2 LST, using long-term continuous ground measurements over vegetated surfaces. MOD11A1 and MOD11B1 LST products were not considered in the current stage due to time limitations. MOD11_L2 LST has been used more frequently than MOD11B1 LST. MOD11A1 LST is reprojected from MOD11_L2 LST. MOD07_L2 LST is also validated because it is one of the input parameters for the MOD11_L2 LST algorithm. It is important to investigate whether the performance of the MOD07_L2 LST algorithm affects that of MOD11_L2 LST. Only nighttime observations were validated in this study because of the limitations of ground measurements. During nighttime, the Earth surface behaves almost as an isothermal and homogeneous surface. During daytime, surface temperatures under shadows are lower than surface temperatures in direct sunlight, giving rise to temperature differences as much as 20 °C (Wan & Dozier, 1996). Ground-measured surface temperatures are only available over one point in each site and cover a small area near the flux tower (about 2–5 m in diameter). Therefore, they may not represent the sunlight and shadow conditions within the MODIS footprint.

This validation study differs from previous MODIS validation works in four aspects. First, this is the first effort to validate MODIS LST products using ground measurements from long-term monitoring sites. The major advantage of using such data is that a large quantity of ground measurements is available. Ground measurements corresponding to more than 1800 MODIS Terra overpasses were used for statistical analysis. Second, the MODIS LST products over vegetated surfaces were evaluated during all seasons. In previous studies, the accuracy of MODIS LST products over vegetated surfaces was validated using ground measurements obtained during growing season only. Third, validation sites from a variety of geographic regions in the U.S. and Germany are used. Therefore, the statistics from the study are potentially more representative than those of previous validation work for vegetated surfaces. Finally, this is the first attempt to evaluate the accuracy of MOD07_L2 LST product by a team that is independent of the MODIS atmosphere team.

2. Data

2.1. Ground measurements

The ground-measured LSTs were obtained from two sources totaling eight sites (see Table 2). The first source of data is the FLUXNET Project, a global network of micrometeorological tower sites that measure the exchanges of carbon dioxide, water vapor, and energy between terrestrial ecosystems and the atmosphere. Some FLUXNET sites in the U.S. are equipped with thermal infra-red (TIR) sensors to continuously measure surface temperature at fixed points (AmeriFlux, 2006). Ground measurements from six FLUXNET sites were used in this study. The land cover types of these sites include grassland, forest, and cropland. The surface temperatures from these sites were measured by Apogee IRTS-P Infra-Red Temperature Sensor (Apogee Instruments Inc., 2005). The sensor is highly water resistant and designed for continuous outdoor use. It uses two type-K thermocouple outputs. The primary thermocouple is used to measure the target temperature. Sensor body temperature is measured using the secondary thermocouple and the sensor body temperature effect is corrected. The spectral range of the sensor is from 6.5 to 14 μm, with an optimal temperature range from − 10 °C

Table 2
Summary of validation sites

Site	Latitude Longitude	Land cover	Canopy height (m)	Elevation (m)	Time period	# of data points	Instrument	Field Of view	Measurement height (m)
Brookings, South Dakota, USA	44.34529 −96.83617	Grassland	0.2–0.4	510	2004/113–2005/62	84	Apogee IR Radiometer	30°	4
Audubon Research Ranch, Arizona USA	31.59073 −110.51038	Grassland	0.1–0.2	985	2002/159–2005/063	466	Apogee IR Radiometer	30°	4
Canaan Valley, West Virginia, USA	39.0633 −79.4208	Grassland	0.1–0.5	988	2004/46–2004/307	36	Apogee IR Radiometer	30°	4
Black Hills, South Dakota, USA	44.15438 −103.6428	Conifer Forest	13–15	About 1700	2001/232–2004/143	126	Apogee IR Radiometer	30°	24
Fort Peck Indian Reservation, Montana, USA	48.30768 −105.10185	Grassland	0.2–0.4	634	2000/61–2005/146	531	Apogee IR Radiometer	30°	3.5
Hainich, Germany	51.07920 10.45218	Mixed broadleaf Forest	33	445	2004/51–2005/147	95	Schulzet radiometer	180°	44.0
Tharandt, Germany	50.96361 13.56694	Conifer Forest	26	380	2004/77–2004/350	82	Heitronics IR pyrometer	Only canopy is viewed	42.0
Bondville, Illinois USA	40.00621 −88.29041	Cropland (corn/soybean)	NA	213	2000/056–2005/050	390	Apogee IR Radiometer	30°	8–10

to 55 °C and an accuracy of ±0.5 °C. The sensor is mounted to look at nadir and has a field of view of 30° in all sites. For the Brookings, Canaan Valley, and Fort Peck grassland sites, the diameter of the sensor footprint is about 2 m (derived from canopy height, measurement height, and field of view). The diameters of the sensor footprints are about 4 and 5 m in the Bondville cropland site and the Black Hills conifer forest site, respectively.

Another data source is the Carbon Europe Integrated Project (CarboEurope-IP, 2006), a program that aims to understand and quantify the present terrestrial carbon balance of Europe and the associated uncertainties at the local, regional and continental scale. Radiative canopy temperature ground measurements from two CarboEurope-IP sites (Hainich and Tharandt, both in Germany), were used in this study. At the Hainich site, radiative canopy temperature was converted from surface upwelling longwave radiation based on Stefan–Boltzmann's law. Surface upwelling radiation was measured by a Schulze net radiometer (model LXG055, Dr Bruno Lange GmbH, Berlin, Germany), which has a spectral range from 0.3 to 100 μm. However, since upwelling shortwave radiation is negligible during nighttime, the measurements represent longwave upwelling radiation only. The instruments are mounted 8 m above the canopy, with a field of view of 180° (lower hemisphere). At the Tharandt site, canopy radiative temperature is measured with a KT15.82D infra-red radiation pyrometer (Heitronics, 2006). The sensor has a spectral range from 8 to 14 μm and a temperature range from − 50 to 1000 °C, with an accuracy better than 0.5 °C. The instrument was vertically mounted, i.e., with a 0° view zenith angle. Since only nighttime observations were considered, the dome heating effect can be ignored in both the Germany sites (Frouin et al., 1988). However, the surface temperature measurements may be influenced by tower installations (Thomas Gruenwald, personal communication).

All ground measurements are half-hourly averaged values. Unity emissivity was assumed in deriving surface temperature. In addition to surface temperatures, downwelling longwave radiation, surface air temperature, soil moisture, relative humidity, and wind speed were simultaneously measured at all sites. Downwelling longwave radiation was used to correct for the reflected downwelling longwave radiation effect (see Section 3). Surface air temperature, humidity, wind speed, and soil moisture, all important factors to LST, were used to analyze the potential factors that contribute to errors in MODIS LST products.

2.2. MODIS products

MOD07_L2 LST is estimated using a statistical regression-based method using 12 MODIS TIR channels, with an option for a subsequent non-linear physical retrieval. The regression

Table 3
Broadband emissivity and related parameters used for deriving broadband emissivity for each site

Site	MOD11_L2			3–14 μm
	Mean nighttime LST (°C)	Emissivity (band 31)	Emissivity (band 32)	Broadband emissivity
Brookings	11.46	0.986	0.990	0.987
Audubon	1.79	0.974	0.987	0.975
Canaan Valley	8.04	0.986	0.990	0.987
Black Hills	12.07	0.988	0.990	0.993
Fort Peck	8.99	0.986	0.990	0.987
Hainich	12.31	0.986	0.990	0.980
Tharandt	13.19	0.987	0.990	0.993
Bondville	10.46	0.986	0.990	0.987

Table 4
Summary of validation results

Site	MOD11_L2 (°C)		MOD07_L2 (°C)	
	Bias (MOD-GT)	RMSE	Bias (MOD-GT)	RMSE
Brookings	0.62	1.63	1.30	1.97
Audubon	0.72	1.31	2.98	3.74
Canaan Valley	0.04	1.42	1.20	2.08
Black Hills	0.15	1.48	3.14	4.10
Fort Peck	−2.19	2.51	0.34	2.70
Hainich	−2.21	2.51	−2.12	2.58
Tharandt	−3.23	3.44	−3.38	3.73
Bondville	−3.09	3.41	−0.16	2.50

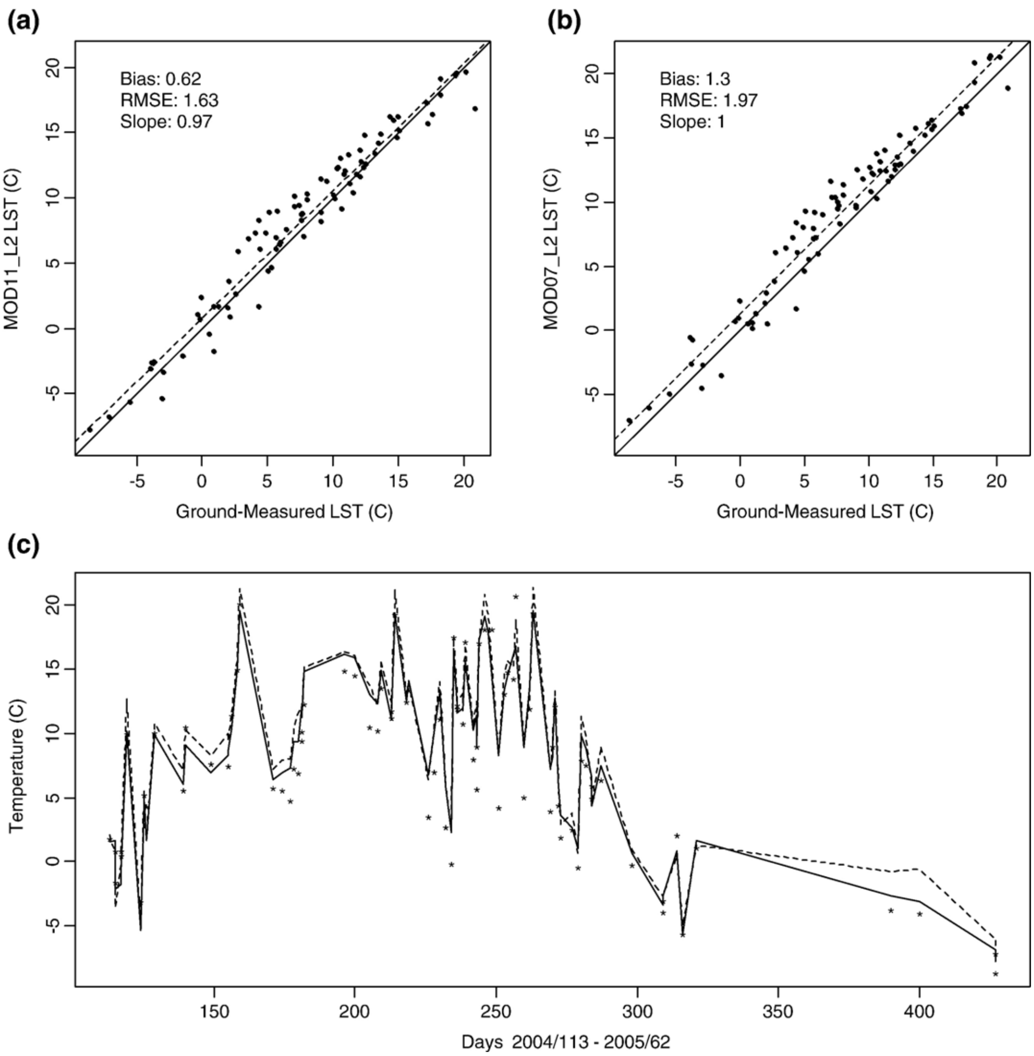

Fig. 1. Plots for Brookings grassland site (a) ground-measured LSTs vs. MOD11_L2 LSTs (b) ground-measured LSTs vs. MOD07_L2 LSTs (c) time series of MOD11_L2 LSTs (solid line), MOD07_L2 LSTs (dash line), and ground-measured LSTs (*).

coefficients for the statistical retrieval are derived using a fast radiative transfer model with atmospheric characteristics taken from a dataset of 12,208 global profiles of atmospheric temperature, moisture, and ozone (Seemann et al., 2003). The spatial resolution is 5 km at nadir. No emissivity information is available in the product. As a secondary variable in the MODIS atmosphere product, MOD07_L2 LST is not as well validated as MOD11_L2 LST. The accuracy of the product may be affected by errors in land surface emissivity (Eva Borbas, personal communication).

MOD11_L2 LST product is retrieved using the generalized split-window algorithm (Wan, 1999; Wan & Dozier, 1996):

$$T_s = C + \left(A_1 + A_2\frac{1-\varepsilon}{\varepsilon} + A_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{31}+T_{32}}{2} + \left(B_1 + B_2\frac{1-\varepsilon}{\varepsilon} + B_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{31}-T_{32}}{2} \quad (1)$$

$$\varepsilon = (\varepsilon_{31} + \varepsilon_{32})/2$$

$$\Delta\varepsilon = \varepsilon_{31} - \varepsilon_{32}$$

where T_s is LST; T_{31} and T_{32} are MODIS band 31 and 32 brightness temperature; ε_{31} and ε_{32} are MODIS band 31 and 32 surface emissivity; C, A_1, A_2, A_3, B_1, B_2, and B_3 are regression coefficients. Multi-dimensional look-up tables (LUTs), based on the results of radiative transfer simulation under a large range of surface and atmospheric conditions, are derived using linear regression. In this algorithm, sensor view zenith angle, MOD07_L2 column water vapor, and MOD07_L2 LST (referred to as atmospheric lower boundary temperature) were incorporated into the LUTs to improve the accuracy of LST retrieval (Wan et al., 2004a,b). MODIS surface emissivity in bands 31 and 32 are available in MOD11_L2 products. They are assigned based on land cover types. Constant emissivity values are used in the view angle range from 0 to 45°. A simple linear scheme is used to scale emissivity when sensor view zenith angle is larger than 45°. It has a 1 km spatial resolution at nadir.

MOD11_L2 (version 4) and MOD07_L2 (version 4) products coincident with ground measurements were acquired through the Earth Observing System Data Gateway (NASA, 2006). The MODIS geolocation product was obtained from the

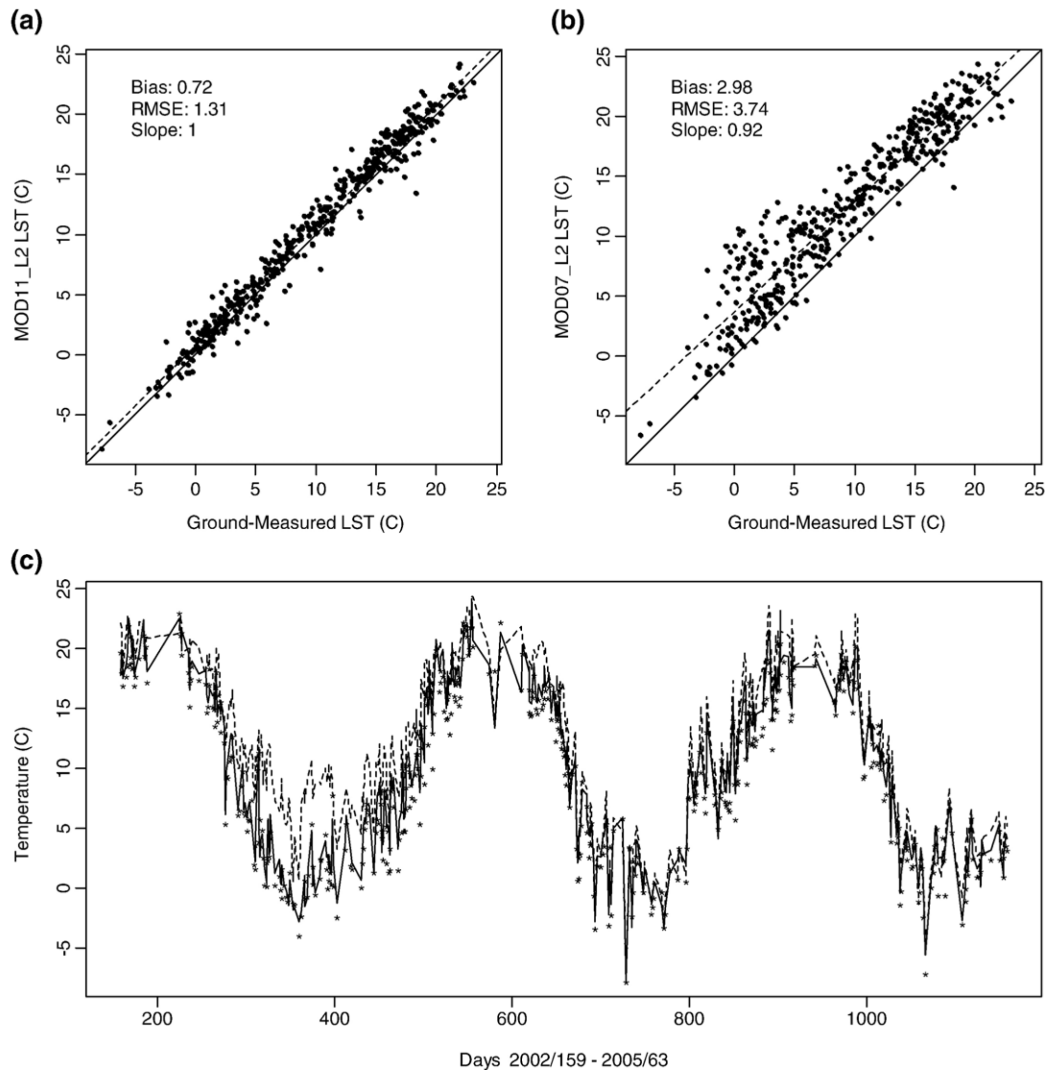

Fig. 2. Plots for Audubon grassland site (a) ground-measured LSTs vs. MOD11_L2 LSTs (b) ground-measured LSTs vs. MOD07_L2 LSTs (c) time series of MOD11_L2 LSTs (solid line), MOD07_L2 LSTs (dash line), and ground-measured LSTs (*).

same source to determine the MODIS LST pixels corresponding to the validation sites. The MOD11_L2 LST, sensor view zenith angle, band 31/32 emissivity, quality control (QC), and MOD07_L2 LST and cloud mask were extracted.

3. Method

Ground-measured surface temperatures from FLUXNET and CarboEurope-IP sites are brightness temperatures in nature, requiring a correction for emissivity effect. Moreover, except for the Tharandt site, the ground instruments in the other seven sites are affected by water vapor. Therefore, the reflected downwelling longwave radiation effect must be considered (Coll et al., 2005; Schmugge et al., 1998; Sobrino et al., 1993). Based on thermal radiative transfer theory, the upwelling longwave radiation at the surface level depends on LST, emissivity, and downwelling longwave radiation (Liang, 2004):

$$F_u = \sigma T_b^4 = (1-\varepsilon)F_d + \varepsilon\sigma T^4 \quad (2)$$

where F_u is surface upwelling longwave radiation, F_d is surface downwelling longwave radiation, ε is broadband emissivity, σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T is LST, and T_b is surface brightness temperature.

In this study, 3–14 μm broadband emissivity for each site was derived using the vegetation spectra from the ASTER Spectral Library (ASTER, 1999), mean nighttime clear sky MOD11_L2 LST, and the retrieved MODIS band 31 (11 μm) and 32 (12 μm) emissivity in the MOD11_L2 product (see Table 3). Specifically, the Johns Hopkins University (JHU) vegetation spectra in the ASTER Spectral Library were used to approximate the emissivity of validation sites. Conifer spectra were used for the Black Hills and Tharandt sites; deciduous spectra were used for the Hainich site; and grass spectra were used for all other sites. Cropland was treated as grassland. Since the vegetation spectra in the spectral library do not exactly match the emissivity used in MODIS LST products, JHU emissivity curves were vertically shifted to match MOD11_L2 band 31 and 32 emissivities. The purpose of shifting JHU spectra is to use similar emissivity values to correct ground-

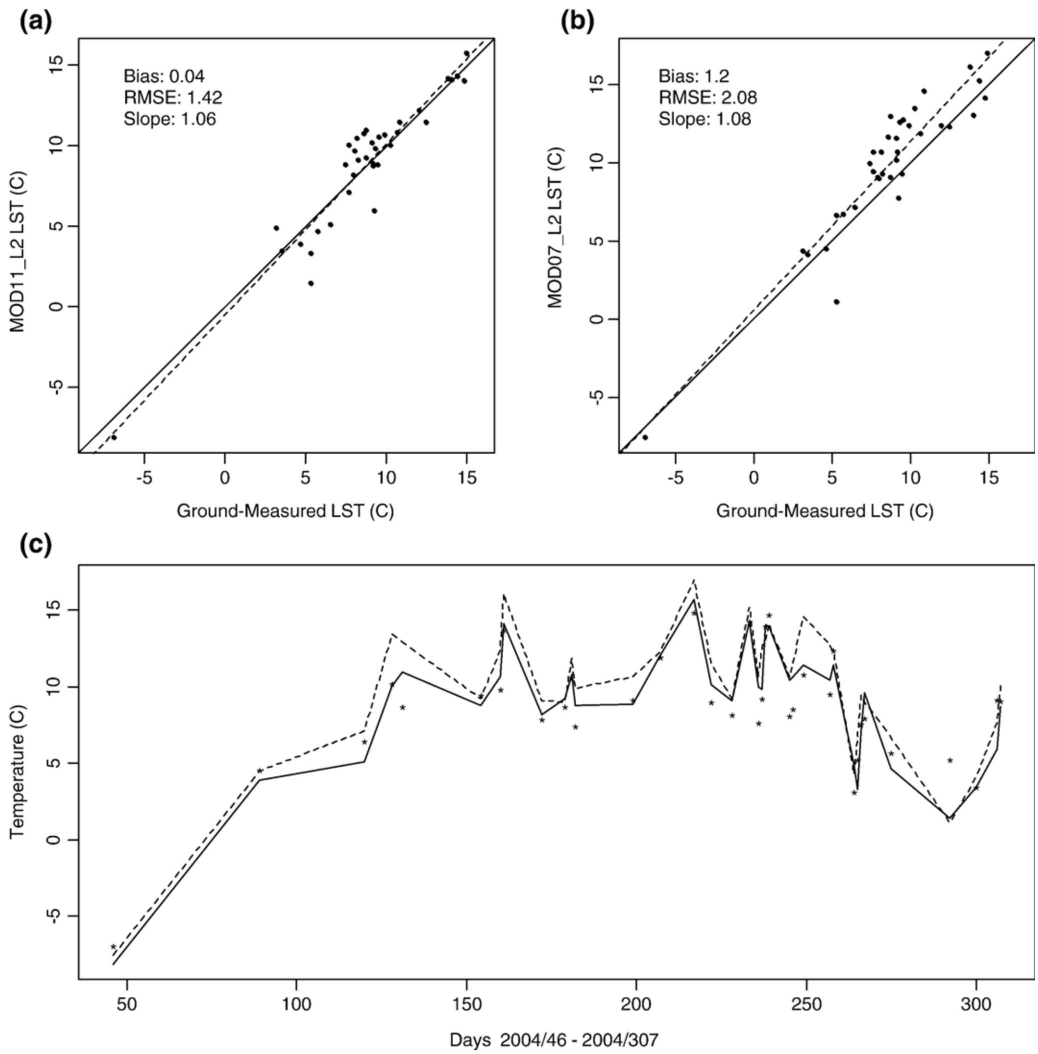

Fig. 3. Plots for Canaan Valley grassland site (a) ground-measured LSTs vs. MOD11_L2 LSTs (b) ground-measured LSTs vs. MOD07_L2 LSTs (c) time series of MOD11_L2 LSTs (solid line), MOD07_L2 LSTs (dash line), and ground-measured LSTs (*).

measured surface temperature as that used in MOD11_L2 product. The derived grassland and forest broadband emissivities are compatible to previous studies (Coll et al., 2005, 2002, 2001). The Audubon site (desert grassland) has a lower broadband emissivity compared with other sites.

Three assumptions were made in correcting ground-measured surface brightness temperatures: (1) All validation sites are Lambertian surfaces. Sobrino et al. (2005) indicate that the emissivity of high vegetation covers show almost Lambertian behavior, with emissivity changes within 0.01 between nadir and 70° view angle. (2) 3–14 μm broadband emissivities are assumed to be equal to the emissivity in the entire longwave range. The radiation of Earth's natural surface materials peaks at about 9.7 μm according to Wien's displacement law. The error caused by this assumption can be ignored. (3) Emissivity is assumed constant over time. Although NDVI has been used to estimate surface emissivity, the formulas are empirically based and good only for the dataset that were used to derive them (van de Griend & Owe, 1993). Besides vegetation density, surface emissivity is also affected by other factors such as precipitation and snow cover, which change frequently over time. It is difficult to obtain accurate emissivity for more than 1800 data points under a wide variety of surface conditions without conducting ground measurements. Over cropland and grassland sites at high latitude, this assumption may cause errors during non-growing seasons because the emissivities of dry grass, leaf-off trees, crop residuals, and bare soil are lower than those of green vegetation.

Ground-measured surface temperatures were first corrected for emissivity and reflected downwelling longwave radiation effects. The corrected surface temperature is referred as "ground-measured LSTs" for convenience. Then, MODIS LSTs were matched with ground-measured LSTs according to the satellite observation time. Satellite observation time was derived by linearly interpolating the start and end time of each MODIS product swath. Ground-measured LSTs are assumed to occur in the middle of each half hour period. Linear interpolation was applied to obtain ground values at the time of satellite overpass. Clear sky observations were identified using MOD11_L2 QC and MOD07_L2 cloud mask. All data

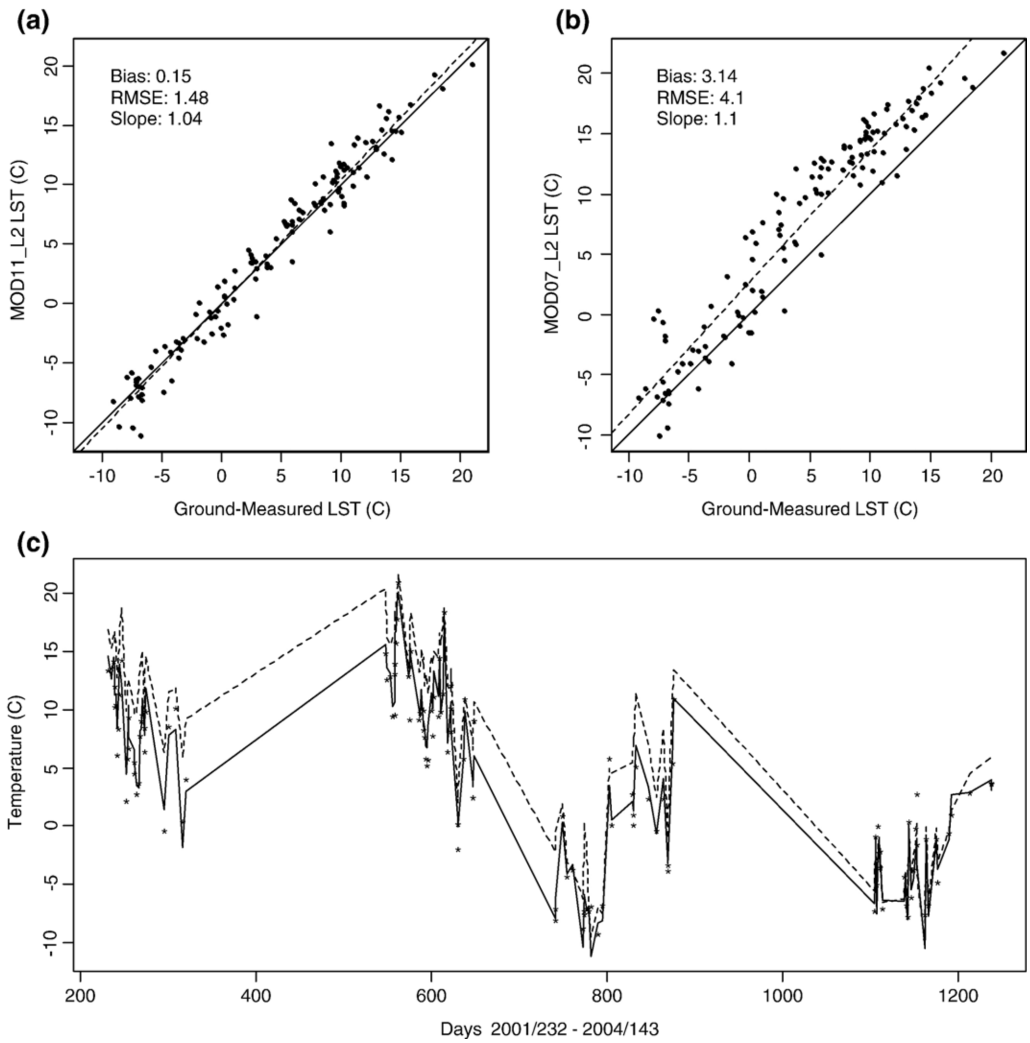

Fig. 4. Plots for Black Hills forest site (a) ground-measured LSTs vs. MOD11_L2 LSTs (b) ground-measured LSTs vs. MOD07_L2 LSTs (c) time series of MOD11_L2 LSTs (solid line), MOD07_L2 LSTs (dash line), and ground-measured LSTs (*).

points were also examined manually to exclude cloud-contaminated MODIS pixels with unreasonably low LST values.

4. Results and discussions

Before presenting and discussing the validation results, the nature of the ground-measured LSTs must be carefully examined. Ground-measured LSTs were only available over one fixed point in each site. Ground measurements are discrete in space, while satellite-derived LSTs are discrete in time. The scale mismatch issue in both space and time must be considered.

One concern is that the small footprints of the ground sensors may not represent the spatial variations in the MODIS footprint. Therefore, ground data used in this study may be less representative of the MODIS footprint than data measured using multiple ground sensors simultaneously (Coll et al., 2005; Wan et al., 2002). However, the footprints of the ground sensors deployed in the validations sites (2–5 m in diameter, see Section 2.1) can represent the variation among the canopies if the canopy is homogeneous. The study has been carefully designed to minimize spatial scale mismatch. Only nighttime ground measurements were used since Earth's surface behaves almost homogeneously at night. Moreover, the temporal averaging of ground measurements can harmonize the two different types of data and further mitigate the scale mismatch issue (Schmetz, 1989). Furthermore, more than 1800 data points were used. The influences of outliers were smaller compared to previous MODIS validation studies that used only a few data points. Therefore, statistics derived from the study can provide useful information about the accuracy of the two MODIS LST products.

Another concern is that the half-hourly averaged ground measurements may not represent the LST at the time of the satellite overpass. LST changes more gradually at nighttime even if there are broken clouds. The MODIS pixels used have been screened using MODIS cloud mask, MOD11_L2 QC information, and manual examination. The effects of clouds in the ground measurements should be small. To further assure that ground measurements do represent the LST at the time of satellite overpass (10:30 pm local time), four half-hourly averaged ground-measured LST closest to the satellite overpass

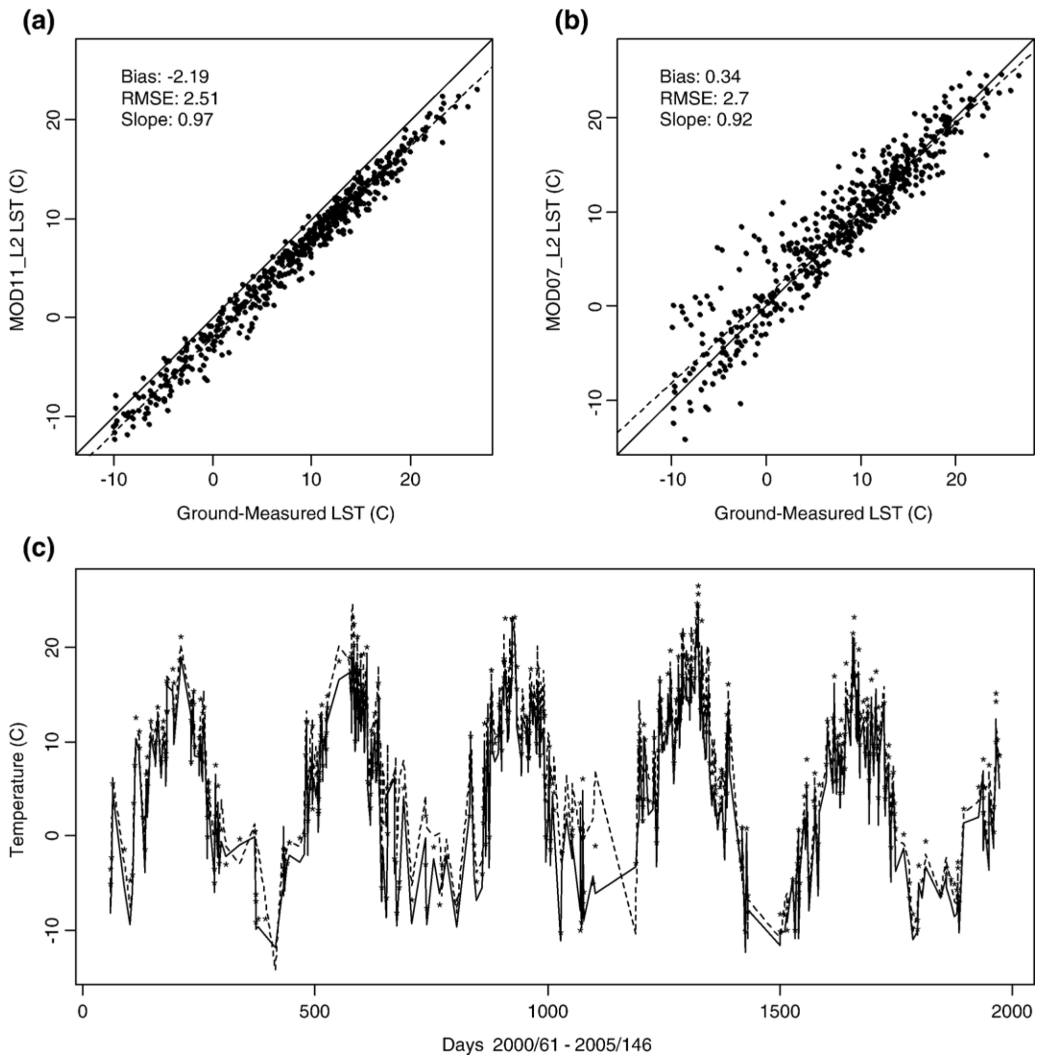

Fig. 5. Plots for Fort Peck grassland site (a) ground-measured LSTs vs. MOD11_L2 LSTs (b) ground-measured LSTs vs. MOD07_L2 LSTs (c) time series of MOD11_L2 LSTs (solid line), MOD07_L2 LSTs (dash line), and ground-measured LSTs (*).

time were obtained for each MODIS clear sky observation. The difference between two consecutive half-hourly averaged values was analyzed. Results show that the differences are less than 1.35 °C with a 95% confidence interval and less than 1 °C with an 89% confidence interval. Errors caused by using half-hourly averaged ground measurements should be small.

4.1. Summary of the results

MOD11_L2 LSTs and MOD07_L2 LSTs were compared to ground-measured LSTs. The biases (MODIS LSTs — ground-measured LSTs) and root mean squared errors (RMSEs) for each site were summarized (see Table 4).

MOD11_L2 LSTs match well with ground measurements in the Brookings (Fig. 1), Audubon (Fig. 2), Canaan Valley (Fig. 3), and Black Hills (Fig. 4) sites, with biases less than 0.8 °C and RMSE less than 1.7 °C. Results at the four sites are generally consistent with previous studies over vegetated surfaces (Coll et al., 2005; Wan et al., 2002) and comparable to the accuracy of ground instruments (0.5 °C) and errors due to using half-hourly ground data. This accuracy is very close to the requirements from user communities (CEOS & WMO, 2000; GCOS, 2006). MOD11_L2 LSTs have larger negative biases (− 2–3 °C) and RMSEs (2.5–3.5 °C) in the other four sites: Fort Peck (Fig. 5), Hainich (Fig. 6), Tharandt (Fig. 7), and Bondville (Fig. 8). However, the accuracy at these four sites agrees with the well-known accuracy of satellite LST products (3–4 °C).

MOD07_L2 LSTs have larger absolute biases and RMSEs than that of MOD11_L2 LSTs in most cases. The biases and RMSEs are relatively small in the Brookings and Canaan Valley sites, with biases less than 1.3 °C and RMSEs less than 2.1 °C. The accuracy of MOD07_L2 LST is lower for the other six sites, however it still agrees with the well-known accuracy of satellite LST products.

4.2. Emissivity issue

The biases and RMSEs presented in this study did not include errors due to the uncertainty in surface emissivity. We assumed a constant emissivity in correcting ground-measured

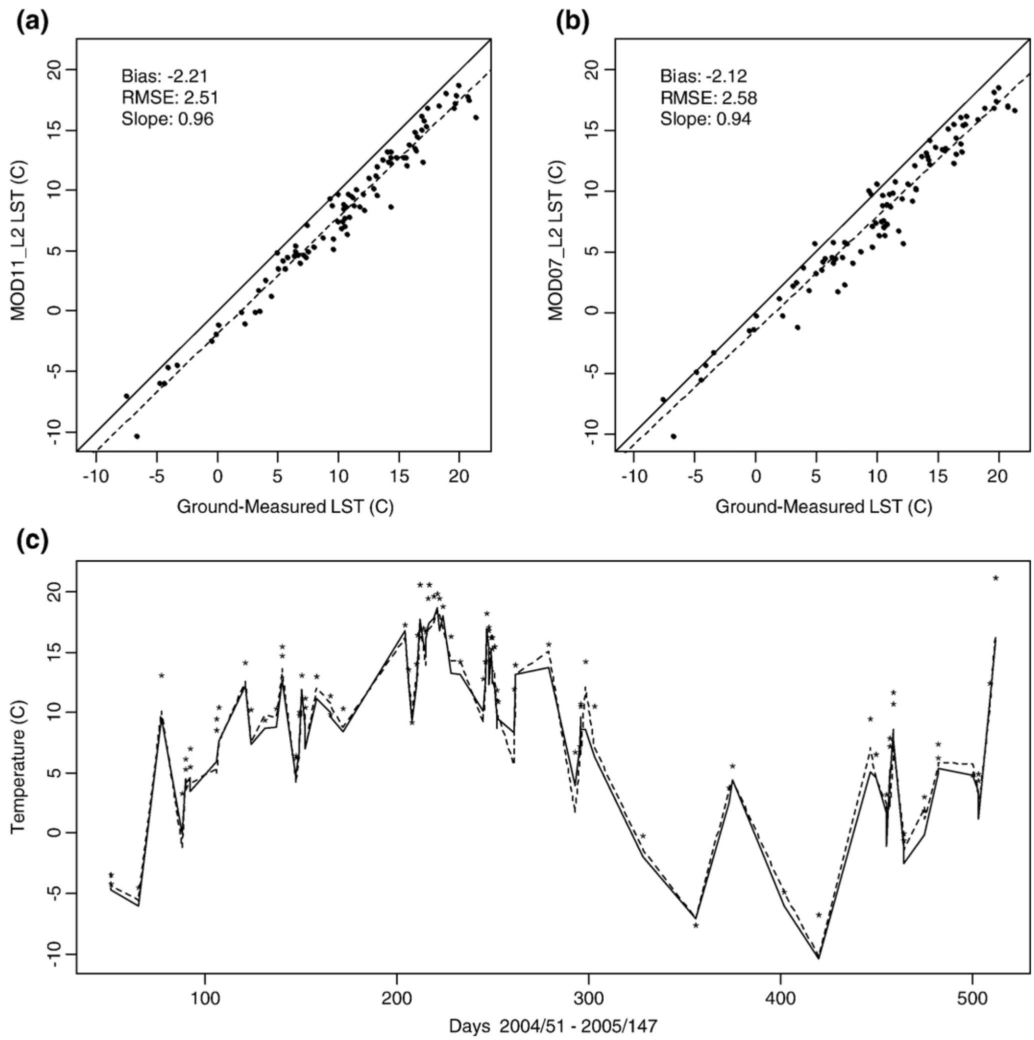

Fig. 6. Plots for Hainich forest site (a) ground-measured LSTs vs. MOD11_L2 LSTs (b) ground-measured LSTs vs. MOD07_L2 LSTs (c) time series of MOD11_L2 LSTs (solid line), MOD07_L2 LSTs (dash line), and ground-measured LSTs (*).

surface temperatures (the assumption made in MOD11_L2 and MOD07_L2 algorithms) because surface emissivity ground measurements are not available. Vegetated sites often have higher emissivities during growing season because green vegetation emissivity is generally higher than dead/leaf-off vegetation or bare ground during winter. However, no obvious trend between bias/RMSE and seasons were observed in the time series graphs (in Figs. 1–8) due to our assumptions about surface emissivity.

Emissivity values used in the study were more representative of the real ground values during growing seasons. During non-growing seasons, the effect of emissivity needs to be considered. The Fort Peck, Hainich, Tharandt, and Bondville sites, in which MOD11_L2 LSTs have negative biases (MODIS — ground-measured) under the current emissivity assumption, will have even larger errors if the actual emissivity is lower during the non-growing season. For the sites with small positive biases, the effect of surface emissivity will be mixed in MOD11_L2 products, depending on the magnitude of errors in emissivity.

4.3. MOD11_L2 LSTs vs. MOD07_L2 LSTs

It is generally expected that the absolute biases and RMSEs in MOD11_L2 LSTs are smaller than those in MOD07_L2 LSTs. The MOD07_L2 LST product is used by the MOD11_L2 generalized split-window algorithm as an input parameter in order to improve its retrieval accuracy. The validation results from this study indicate that the MOD07_L2 LST product may contribute to the improved accuracy in the MOD11_L2 LST product. Another factor that may cause differences in validation results is spatial resolution. MOD07_L2 LSTs have a coarser spatial resolution than MOD11_L2 LST. Although spatial scale mismatch is mitigated here, it cannot be eliminated. The ground measurements were more representative of the 1 km MOD11_L2 pixels than the 5 km MOD07_L2 pixels.

The relationships between the biases in MOD11_L2 LST and those in MOD07_L2 LST for the eight sites were analyzed using linear regression. The biases in the two products are correlated, with a correlation coefficient of 0.7 and a significance level of 99% (see Fig. 9). Although only eight

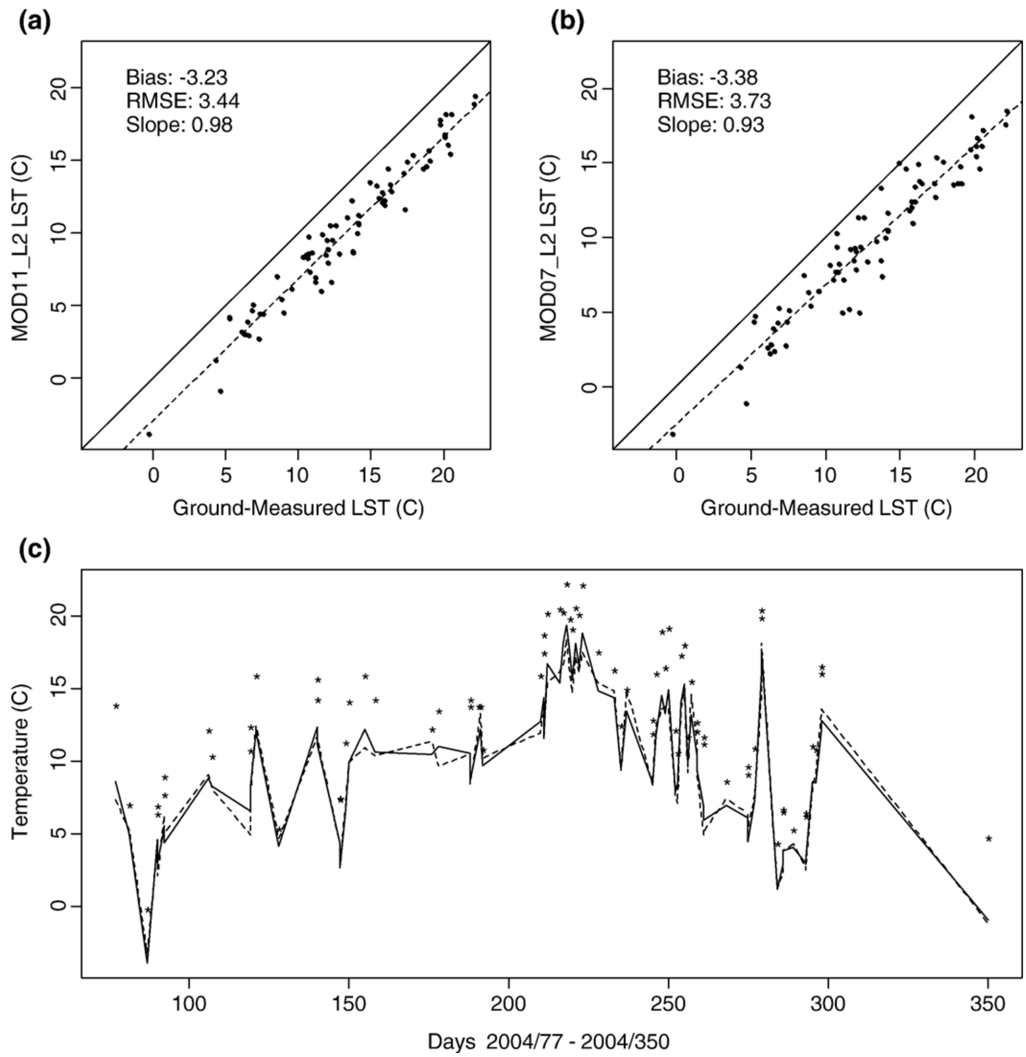

Fig. 7. Plots for Tharandt forest site (a) ground-measured LSTs vs. MOD11_L2 LSTs (b) ground-measured LSTs vs. MOD07_L2 LSTs (c) time series of MOD11_L2 LSTs (solid line), MOD07_L2 LSTs (dash line), and ground-measured LSTs (*).

sites were used in the study, the observed trend indicated that biases in MOD07_L2 LSTs may influence the accuracy of MOD11_L2 LSTs, at least partly. MOD11_L2 LSTs match well with ground-measured LSTs (biases <0.8 °C) when the biases in MOD07_L2 LSTs are greater than 1 °C; MOD11_L2 LSTs are underestimated by 2.5–3.5 °C when the biases in MOD07_L2 LSTs are less than 1 °C.

4.4. Dependence of LST errors on sensor view zenith angle, surface air temperature, humidity, wind speed, and soil moisture

To analyze the potential factors that may cause large errors at certain sites, the relationships between the errors (absolute differences between MODIS LSTs and ground-measured LSTs) and sensor view zenith angle (θ), surface air temperature, humidity, wind speed, and soil moisture were investigated using ground measurements from the Bondville, Audubon, and Fort Peck sites. The other five sites do not have sufficient ground-measurements for statistical analysis. Scatterplots between the errors and these variables in the Fort Peck site are presented (see Fig. 10). Similar patterns were observed at the other two sites.

Statistics show the average errors for observations acquired under lower view zenith angles ($\theta <= 30°$) are 0.5–0.8 °C lower than those acquired at greater view zenith angles ($\theta > 30°$) for both products. Greater errors for LST under larger sensor view zenith angles were also observed in the validation study conducted by Coll et al. (2005). The pattern is due to the difference in view zenith angles between ground instruments and the MODIS sensor. Ground-measured LSTs were obtained at 0° view zenith angles, while MODIS observations were acquired at a large range of view zenith angles (0–65°).

The errors in two LST products were independent of surface air temperature, humidity, wind speed, and soil moisture (correlation coefficients <0.03). However, there are considerably more cases with larger errors (>4 °C) under low wind speed and/or low humidity conditions. The lack of correlation between errors and soil moisture may be explained by the nature of the validation sites. Audubon is a desert grassland site where background soil moisture changes little over time; the other two

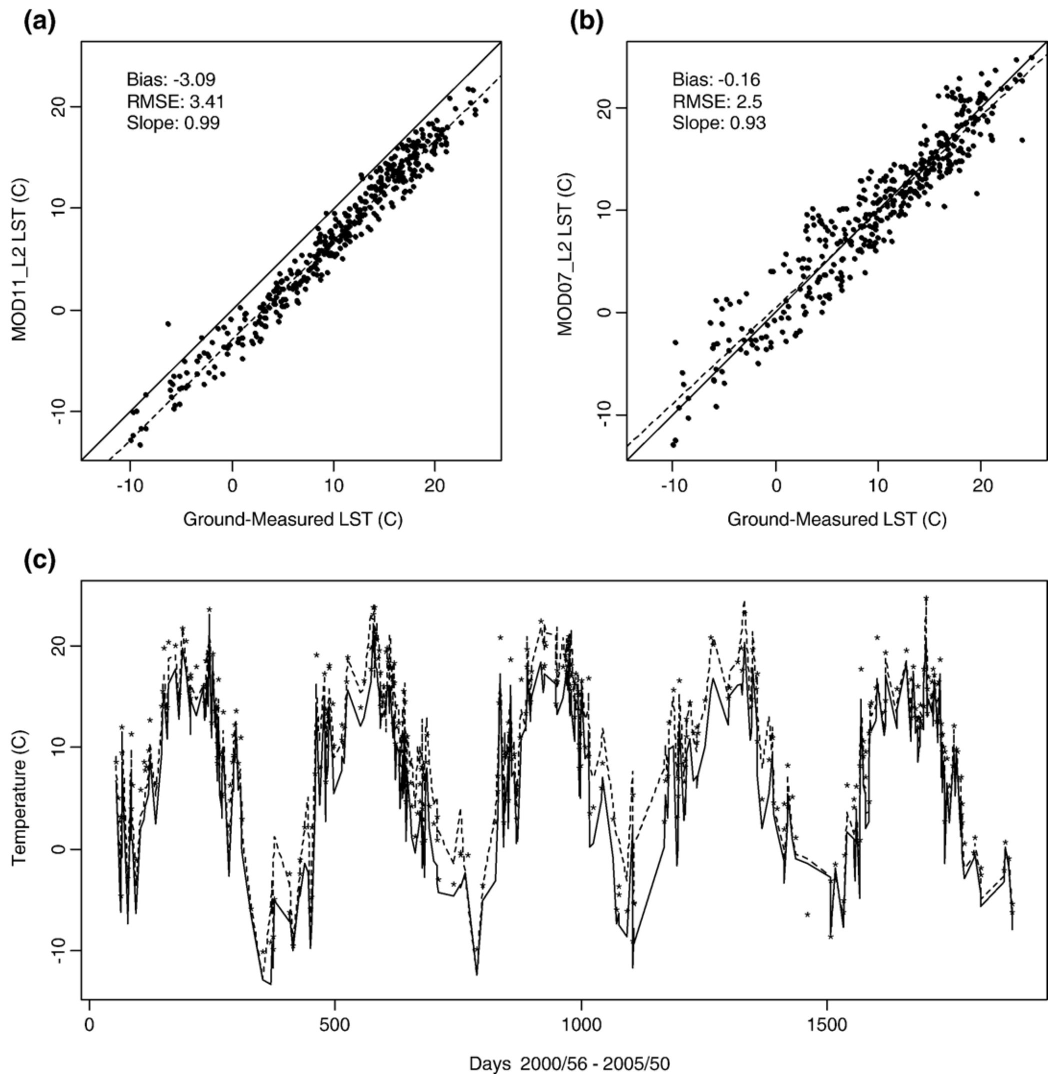

Fig. 8. Plots for Bondville cropland site (a) ground-measured LSTs vs. MOD11_L2 LSTs (b) ground-measured LSTs vs. MOD07_L2 LSTs (c) time series of MOD11_L2 LSTs (solid line), MOD07_L2 LSTs (dash line), and ground-measured LSTs (*).

sites are densely vegetated during growing season and covered by dry grass or crop residuals during non-growing seasons. Therefore, little background soil can be observed by the sensors.

More ground information is needed to identify the factors that cause large errors at the Fort Peck, Hainich, Tharandt, and Bondville sites. The larger negative biases in the MOD11_L2 LSTs at these sites may be partly due to the internal relationship between MOD07_L2 and MOD11_L2 products (see Section 4.3). Ground instrument calibration and tower installations may also contribute to errors. It is also worth noting that the Fort Peck and Canaan Valley sites have similar land cover types, mean nighttime temperatures, and emissivities; however, the Fort Peck site has a much larger bias and RMSE than the Canaan Valley site.

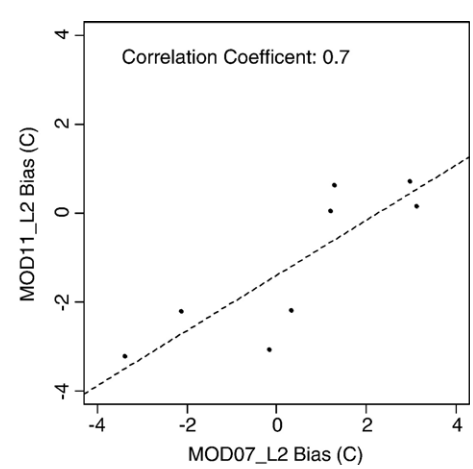

Fig. 9. The relationship between MOD07_L2 and MOD11_L2 biases. Each dot in the plot represents the bias at a validation site.

5. Summary

LST is a key variable for climatological and environmental studies. The MODIS science team provides multiple daily LST

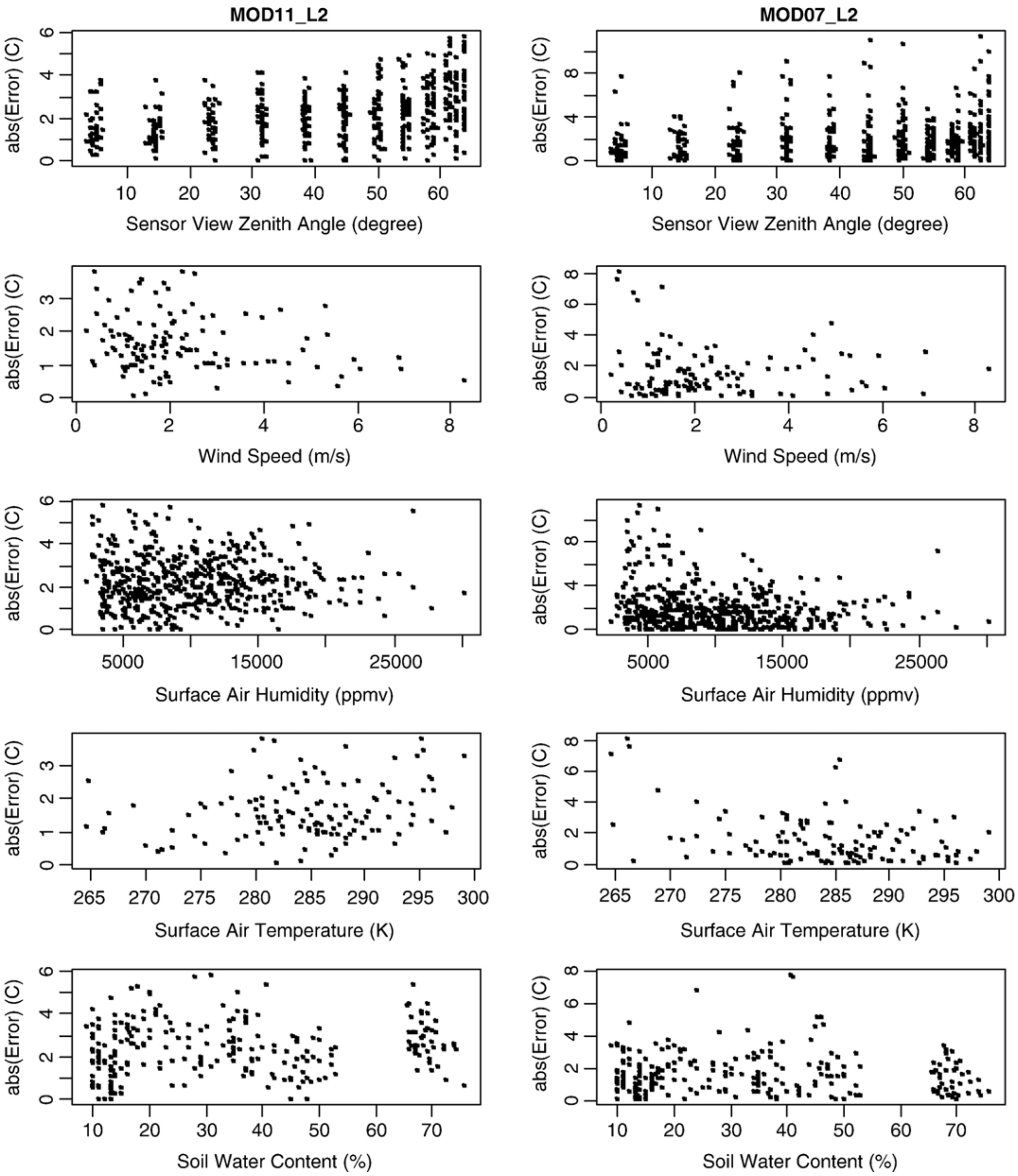

Fig. 10. The relationship between errors and sensor view zenith angle, surface air temperature, surface air humidity (ground-measured relative humidity was converted to volume mixing ratio), wind speed, and soil water content.

products on a global scale. However, product quality requires more assessment so that uncertainty in the products does not limit more widespread application of the data. In this study, two MODIS products, MOD11_L2 and MOD07_L2, were examined using long-term ground measurements from the FLUXNET and CarboEurope-IP networks. Only nighttime observations were used in this study to mitigate the scale mismatch issue between point ground measurements and the MODIS footprint.

Initial results show that MOD11_L2 LSTs have smaller absolute biases and RMSEs than those of MOD07_L2 LSTs in most cases. MOD11_L2 LSTs match well with ground measurements in the Brookings, Audubon, Canaan Valley, and Black Hills sites, with absolute biases less than 0.8 °C and RMSEs less than 1.7 °C. This accuracy is very close to the requirements from user communities. For the Fort Peck, Hainich, Tharandt, and Bondville sites, MOD11_L2 LSTs were underestimated by 2–3 °C. Biases in MOD11_L2 LSTs correlate to those of MOD07_L2 LSTs. Since the MOD07_L2 LST product is one of the input parameters of the MOD11_L2 LST algorithm, biases in MOD11_L2 LSTs may be influenced by the biases in MOD07_L2 LSTs. The errors in both products weakly depend on sensor view zenith angle and are independent of surface air temperature, humidity, wind speed, and soil moisture.

Only one cropland site was investigated in the current stage. More such sites are needed for reliable validation results over cropland. Moreover, a large portion of Earth's surface consists of bare ground. Consequently, bare ground sites need to be investigated in the future studies. The accuracy of MODIS LST products during daytime is as important as those during nighttime. Only nighttime MODIS products have been validated because of the limitation of available ground measurements in this study. More work is needed to validate the performance of MODIS LST products during daytime.

Acknowledgements

This study is funded by the NASA grant NNG04GL85G. We would like to thank Dr. Paul Menzel and Ms. Eva Borbas for providing the information about MOD07_L2 surface temperature product, Dr. Corinna Rebmann for providing the ground measurements information about the Hainich, Germany site, and Dr. Thomas Grünwald and Dr. Christian Bernhofer for providing ground measurement information about the Tharandt, Germany site. We would also like to thank the anonymous reviewers and Dr. Kaicun Wang, who provided valuable comments and suggestions that greatly improved the quality of the manuscript.

References

AmeriFlux. (2006). http://public.ornl.gov/ameriflux/data-handler.cfm [visited May 1, 2006].

Apogee Instruments Inc. (2005). http://www.apogee-inst.com/pdf_files/irtp3.pdf [visited Aug. 16, 2005].

ASTER. (1999). http://speclib.jpl.nasa.gov/ [visited Nov. 30, 2005].

CarboEurope-IP. (2006). http://www.carboeurope.org/ [visited Mar. 28, 2007].

CEOS, and WMO. (2000). http://192.91.247.60/sat/aspscripts/Requirement-search.asp [visited Feb. 7, 2007].

Coll, C., Caselles, V., Rubio, E., Sospedra, F., & Valor, E. (2001). Analysis of thermal infrared data from the Digital Airborne Imaging Spectrometer. *International Journal of Remote Sensing*, *22*, 3703−3718.

Coll, C., Caselles, V., Rubio, E., Valor, E., Sospedra, F., Baret, F., et al. (2002). Temperature and emissivity extracted from airborne multi-channel data in the ReSeDA experiment. *Agronomie*, *22*, 567−573.

Coll, C., Valor, E., Niclòs, R., Sánchez, J. M., Rivas, R., Caselles, V., et al. (2005). Ground measurements for the validation of land surface temperatures derived from AATSR and MODIS data. *Remote Sensing of Environment*, *97*(3), 288−300.

Frouin, R., Gautier, C., & Morcrette, J. J. (1988). Downward longwave irradiance at the ocean surface from satellite data: Methodology and in situ validation. *Journal of Geophysical Research*, *93*(C1), 597−619.

GCOS. (2006). *Systematic observation requirements for satellite-based products for climate-supplemental details to the satellite-based component of the implementation plan for the global observing system for climate in support of the UNFCCC.* The Global Climate Observation System GCOS-107 http://www.wmo.ch/web/gcos/Publications/gcos-107.pdf

Heitronics. (2006). http://www.heitronics.com/english2/indexe.htm [visited Feb. 13, 2007].

Liang, S. (2001). An optimization algorithm for separating land surface temperature and emissivity from multispectral thermal infrared imagery. *IEEE Transactions on Geoscience and Remote Sensing*, *39*(2), 264−274.

Liang, S. (2004). Quantitative remote sensing of land surfaces. In J. A. Kong (Ed.), *Wiley series in remote sensing.* Jew Jersey: John Wiley & Sons.

Menzel, W. P., Seemann, S. W., Li, J., & Gumley, L. E. (2002). *MODIS atmospheric profile retrieval algorithm theoretical basis document. University of Wisconsin–Madison.*

Mostovoy, G. V., Filippova, M. G., King, R. L., Reddy, K. R., & Kakani, V. G. (2006). Statistical estimation of daily maximum and minimum air temperatures from MODIS LST data over the state of Mississippi. *GIScience and Remote Sensing*, *43*(1), 78−110.

Nagler, P. L., Cleverly, J., Glenn, E., Lampkin, D., Huete, A., & Wan, Z. (2005). Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. *Remote Sensing of Environment*, *94*(1), 17−30.

NASA. (2006). http://delenn.gsfc.nasa.gov/~imswww/pub/imswelcome/ [visited May 31, 2006].

Peres, L. F., & DaCamara, C. C. (2004). Land surface temperature and emissivity estimation based on the two-temperature method: Sensitivity analysis using simulated MSG/SEVIRI data. *Remote Sensing of Environment*, *91*(3–4), 377−389.

Pinheiro, A. C. T., Privette, J. L., Mahoney, R., & Tucker, C. J. (2004). Directional effects in a daily AVHRR land surface temperature dataset over Africa. *IEEE Transactions on Geoscience and Remote Sensing*, *42*(9), 1941−1954.

Schmetz, J. (1989). Towards a surface radiation climatology: Retrieval of downward irradiances from satellites. *Atmospheric Research*, *23*(3–4), 287−321.

Schmugge, T., Hook, S. J., & Coll, C. (1998). Recovering surface temperature and emissivity from thermal infrared multispectral data. *Remote Sensing of Environment*, *65*(2), 121−131.

Seemann, S. W., Li, J., & Menzel, W. P. (2003). Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances. *Journal of Applied Meteorology*, *42*(8), 1072−1091.

Sobrino, José A., Jiménez-Muñoz, Juan C., & Verhoef, Wout (2005). Canopy directional emissivity: Comparison between models. *Remote Sensing of Environment*, *99*(3), 304−314.

Sobrino, J. A., Li, Z. -L., & Stoll, M. P. (1993). Impact of the atmospheric transmittance and total water vapor continent in the algorithms for estimating satellite sea surface temperatures. *IEEE Transactions on Geoscience and Remote Sensing*, *31*(5), 946−953.

Sun, Y. -J., Wang, J. -F., Zhang, R. -H., Gillies, R. R., Xue, Y., & Bo, Y. -C. (2005). Air temperature retrieval from remote sensing data based on thermodynamics. *Theoretical and Applied Climatology*, *80*(1), 37.

Tran, H. (2006). Assessment with satellite data of the urban heat island effects in Asian mega cities. *International Journal of Applied Earth Observation and Geoinformation*, *8*(1), 34.

van de Griend, A. A., & Owe, M. (1993). On the relationship between thermal emissivity and the normalized difference vegetation index for natural surfaces. *International Journal of Remote Sensing*, *14*(6), 1119−1131.

Wan, Z. (1999). *MODIS land-surface temperature algorithm theoretical basis document (LST ATBD):Version 3.3.* Santa Barbara: University of California http://modis.gsfc.nasa.gov/data/atbd/atbd_mod11.pdf

Wan, Z., & Dozier, J. (1996). A generalized split-window algorithm for retrieving land-surface temperature from space. *IEEE Transactions on Geoscience and Remote Sensing*, *34*(4), 892−905.

Wan, Z., & Li, Z. -L. (1997). A physics-based algorithm for retrieving land-surface emissivity and temperature from EOS/MODIS data. *IEEE Transactions on Geoscience and Remote Sensing*, *35*(4), 980−996.

Wan, Z., & Li, Z. -L. (1997). A physics-based algorithm for retrieving land-surface emissivity and temperature from EOS/MODIS data. *IEEE Transactions on Geoscience and Remote Sensing*, *35*(4), 980−996.

Wan, Z., Wang, P., & Li, X. (2004). Using MODIS land surface temperature and normalized difference vegetation index products for monitoring drought in the southern Great Plains, USA. *International Journal of Remote Sensing*, *25*(1), 61−72.

Wan, Z., Zhang, Y., Zhang, Q., & Li, Z. L. (2004). Quality assessment and validation of the MODIS global land surface temperature. *International Journal of Remote Sensing*, *25*(1), 261−274.

Wan, Z., Zhang, Y., Zhang, Q., & Li, Z. -L. (2002). Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data. *Remote Sensing of Environment*, *83*(1–2), 163−180.

Wang, K., Li, Z., & Cribb, M. (2006). Estimation of evaporative fraction from a combination of day and night land surface temperatures and NDVI: A new method to determine the Priestley–Taylor parameter. *Remote Sensing of Environment*, *102*(3–4), 293−305.

Wang, K., Wan, Z., Wang, P., Sparrow, M., Liu, J., Zhou, X., et al. (2005). Estimation of surface long wave radiation and broadband emissivity using Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature/emissivity products. *Journal of Geophysical Research*, *110* (D11109). doi:10.1029/2004JD005566