Validation of MODIS land surface temperature products using ground measurements in the Heihe River Basin, China

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ABSTRACT

It is very necessary to validate MODIS land surface temperature (LST) for its application, especially in the arid and semi-arid regions. In this study, the Terra and Aqua MODIS 1km daily LST products (MOD/MYD11A1) are validated using ground based longwave radiation observation. The longwave radiation ground measurements during 2008 to 2009 were collected from four automatic weather stations in the Heihe River Basin. In this validation process, the land surface broadband emissivities of the validation stations were obtained from ASTER Spectral library. Then the ground-measured LSTs of validation stations were converted from surface longwave radiation based on Stefan-Boltzmann's law and thermal radioactive transfer theory. The validation results indicated that: except for DYKGT station, the mean bias was less then 1K and the mean absolute error (MAE) range was about 2-3K; MYD11A1 LSTs from Aqua have larger biases, MAEs, and RMSDs than that of MOD11A1 LSTs from Terra in most cases. The comparisons with ground measured LSTs show that the MAEs and RMSDs from daytime MOD/MYD11A1 comparisons are larger than that from nighttime MOD/MYD11A1 comparisons.

Keywords: MODIS, validation, longwave radiation, Heihe River Basin, land surface temperature

1 INTRODUCTION

Land surface temperature (LST) is a key variable in climatological and environmental studies, and a major controlling factor of global climate and environmental changes[1-6]. It reflects energy factor at the earth-atmosphere interface, and greatly affects the land surface processes. The traditional method to obtain LST is based on ground observation of the meteorological stations. It is difficult to obtain accurate spatial continuous LST at regional scale, because of the high surface heterogeneity, which leads to the difficult application in large scale based on the station observations data. In contrast, the land surface temperatures retrieved from remote sensing data can afford spatial continuous distributed data. Therefore, the remote sensing-based LST product has become an alternative data source in the large scale researches. The daily MODIS LST products are calculated and afforded by Earth Observing System Data and Information System (EOSDIS) [6]. These data sets can provide four times land surface temperature one day at global scale.

Meteorological, hydrological, and agricultural researches require an accuracy of 0.5-2°C for LST retrieved from satellite observation at 1-10 km spatial resolution[7, 8]. When using MODIS LST in these researches, uncertainties in MODIS LST must be well assessed. Validation of MODIS LST can give useful information to data users and producers. MODIS LST products have been validated in previous studies[9-16]. However, these products have not been adequately validated in the arid and semi-arid regions where MODIS LST has lower accuracy compare to other regions. This paper focuses on using longwave radiation from ground measurements data to validate MODIS LST 1km daily products (MOD/MYD11A1) in the Heihe River Basin. Heihe River Basin is the second large inland river basin of China located in Chinese arid region. MODIS can provide multiple daily land surface temperature, the key environment factor for drought monitor and climate change research in this region. Therefore the validation is very important for MODIS LST application in this region. The longwave radiation data were firstly used to validate MODIS LST in this region. The total accuracy of MODIS LSTs of this region was discussed. Moreover, LST in daytime, LST in nighttime, LST form Terra and LST from Aqua were separately validated using longwave radiation data.

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2 DATA AND PROCESSING

2.1 data

The ground measurements employed in this study were derived from four super stations (including: Automatic Weather Station (AWS), Eddy Covariance (EC) and Soil Observation (SO)) in Watershed Allied Telemetry Experimental Research (WATER) [17]. Fig.1 and Table 1 show the information of the validation region and stations. The longwave radiation data with a temporal resolution of 10 minutes from 2008 to 2009 was provided by Environmental and Ecological Science Data Center for West China.

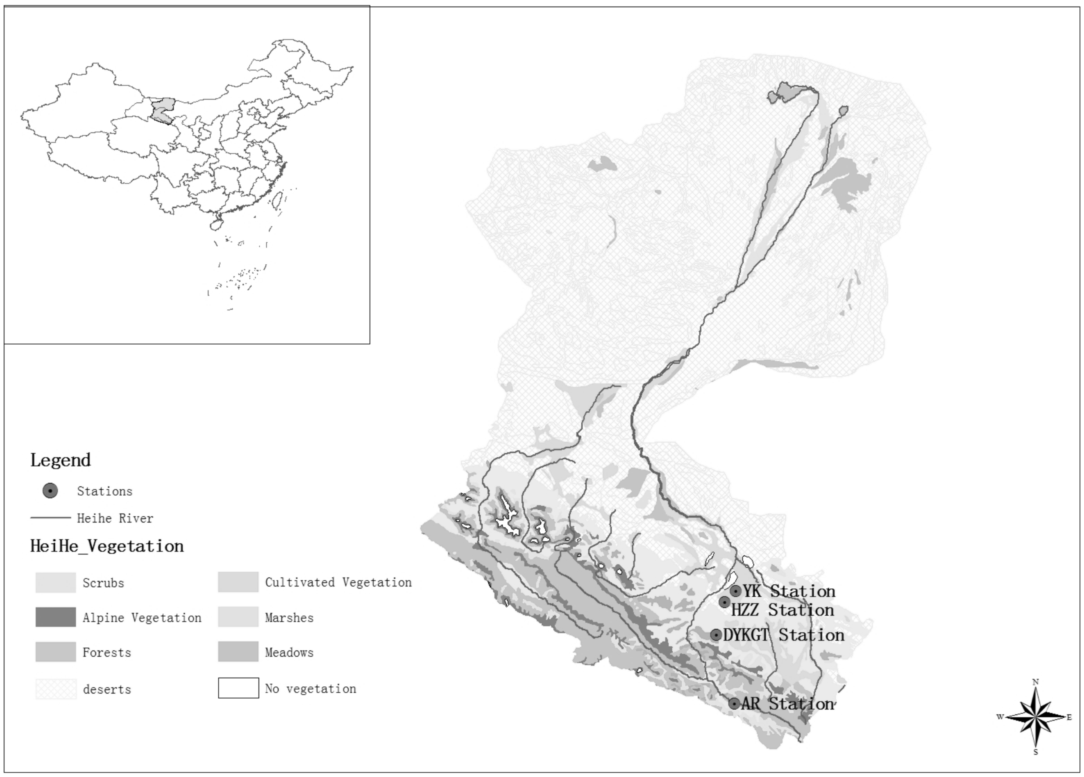

Figure 1. Map of the four super stations (YK station, HZZ Station, DYKGT Station and AR Station) in WATER

Table 1 Information of validation sites

Site	Latitude	Longitude	Elevation (m)	Land cover	Instrument Type	Instrument supplier	Instrument precision	Height (m)
AR	N38.04439	E100.46469	3032.8	Grassland	PIR	EPPLEY(America)	±5%	1.50
HZZ	N38.76520	E100.31858	1726	Desert	CG3	CAMPBELL(America)	±10%	1.50
DYKGT	N38.53369	E100.25022	2835.2	Conifer Forest	CG3	CAMPBELL(America)	±10%	19.7
YK	N38.85714	E100.41033	1519.1	Cropland	CG3	CAMPBELL(America)	±10%	4.00

*AR: A'rou freeze/thaw observation; HZZ: Huazhaizi desert station; BG: Binggou cold region hydrometeological station; DYKGT: Dayekou Guantan forest station; YK: Yingke oasis station.

In this work, the latest MODIS products version V005 (MOD/MYD11A1) of Heihe River Basin from 2008 to 2009 were downloaded from EOSDIS for the validation research. The data quality of this version data was improved significantly. In addition to each HDF file, an XML file is provided with metadata, from which the important fields can be obtained, such as "RangeBeginningTime", "RangeEndingTime", "QAPercentCloudCover", "DayNightflag", "QAPercentMissingData", "PGEVersion". The processed MODIS data is usually made available for download on a

NASA FTP server few minutes after image acquisition. There are twelve fields in MODIS LST products. Besides the LST field, the quality control (QC) field and view time (local time) field are both important for the validation study. High quality MODIS LST data was extracted according to QC field at the validation sites, and ground observing LST corresponding to MODIS view time was picked out to validate MODIS LST.

ASTER Spectral Library is constructed by the Jet Propulsion Laboratory, California Institute of Technology[18]. The ASTER Spectral Library includes data from three other spectral libraries: the Johns Hopkins University (JHU) Spectral Library, the Jet Propulsion Laboratory (JPL) Spectral Library, and the United States Geological Survey (USGS - Reston) Spectral Library[19]. The latest (the version2.0) spectral library released in 2008 was used in this work. It totally includes eight classes, over 2400 spectral data of natural and manmade materials. According to the Land cover types, the vegetation spectral data of each station was obtained from the ASTER Spectral Library. Then the broadband emissivity of each station was retrieved from vegetation spectral data.

2.2 Data processing

The values of the MODIS LST products were picked out according the location information of each station. Although there are totally four times of LST data one day, clouds and other atmospheric disturbance often obscure parts or even the entirety of these satellite images. Consequently, the quality assurance information of the LST scientific data sets should be used to help determine the usefulness of the LST data. In this study, the data were selected with 0 in quality control field, e.g., 00 in "Mandatory QA flags", 00 in "Data quality flag", average error of emissivity <=0.01, average error of land surface temperature<=1K. The temporal resolution of ground measurements is 10min.The ground measured data of the upwelling longwave and downwelling longwave radiations selected was closest to the satellite overpass the time in 10min. 3–14 μm broadband emissivities for stations were derived using the vegetation spectra from the ASTER Spectral Library base on the vegetation types in the station. For vegetated sites, with the view of the usually unknown land surface emissivity, the validation using the ground data is limited to the growing season.

3 METHODOLOGY

The LST was calculated from surface upwelling longwave radiation based on Stefan-Boltzmann's law. All ground measurements are ten minutes average value. Based on thermal radioactive transfer theory, the upwelling longwave radiation at the surface level can be calculated depending on LST, emissivity, and downwelling radiation [16, 20]:

$$F_u = \delta T_b^4 = (1-\varepsilon)F_d + \varepsilon\delta T^4 \tag{1}$$

Where F_u [w/m^2] is surface upwelling longwave radiation; F_d [w/m^2] is surface downwelling longwave radiation; ε is broadband emissivity; δ is the Stefan-Boltzmann constant (5.67×10^{-8} Wm^{-2}K^{-4}); T [K] is LST, and T_b [K] is surface brightness temperature. The broadband emissivity for each site was derived from the vegetation spectra in ASTER Spectral Library. Then the results calculated by Eq. (1) were used to validate MODIS LST products. The bias and mean absolute error (*MAE*) are used to estimate the difference between MODIS LST products and the ground measurements. They can be expressed in the Eq. (2) and Eq. (3). The root mean square deviation (*RMSD*) that expressed in Eq. (4) is used to evaluate the discrete between MODIS LST products and the ground measurements.

$$Bias = \frac{1}{n}\sum_{i=0}^{n}\left(LST_{MODIS(i)} - LST_{MS(i)}\right) \tag{2}$$

$$MAE = \frac{1}{n}\sum_{i=0}^{n}\left|LST_{MODIS(i)} - LST_{MS(i)}\right| \tag{3}$$

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(LST_{MODIS(i)} - LST_{MS(i)})^2} \tag{4}$$

Where $LST_{MODIS(i)}$ (K) is MODIS LST; $LST_{MS(i)}$ (K) is ground measurement which is matched with $LST_{MODIS(i)}$ according to the satellite observation time.

4 RESULTS

The comparison results between MOD/MYD11A1 LSTs and ground-measured LSTs are shown in Figure 2. The statistical results (MODIS LST vs. Ground-measured LST), using biases, MAEs, and RMSDs for each site, are summarized in Table 2. The total validation results of MODIS LST in the four stations indicate that MOD/ MYD11A1 LSTs match well with ground measurements in AR, HZZ and YK stations, with biases less than 0.6K, MAE less than 2.8K, and RMSD less than 4K. In these sites MOD/MYD11A1 LSTs are a few Kelvin degrees lower than the ground-measured LSTs in average level and the linear fitting lines are close to the 1:1 line. In the DYKGT station (DYKGT), MOD/MYD11A1 LSTs have been larger positive biases (1.95K), MAEs (3.26K), and RMSDs (4.34K).

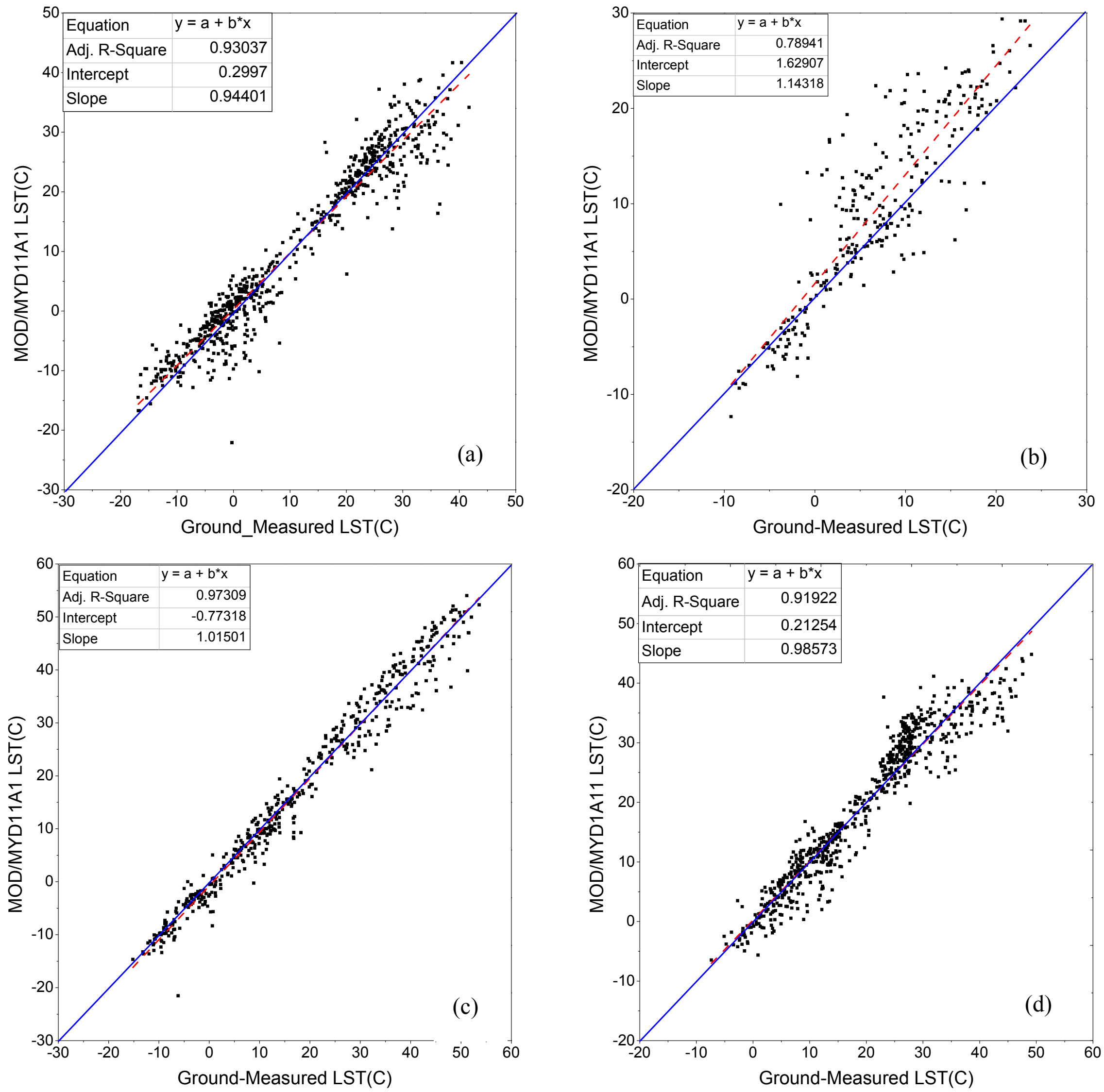

Figure 2. Plots for all sites ground-measured LSTs vs. MOD/MYD11A1 LSTs

(a) Plots for A'rou freeze /thaw observation station (AR station).

(b) Plots for Dayekou Guantan forest station (DYKGT station).

(c) Plots for Huazhaizi desert station (HZZ station).

(d) plots for Yingke oasis station (YK station)

Table 2 Summary of validation results

Sites	total number	Total(K)			Terra(K)			Aqua(K)			Night(K)			Day(K)		
		Bias (MOD -GM)	MAE	RMSD	Bias (MOD -GM)	MAE	RMSD	Bias (MOD -GM)	MAE	RMSD	Bias (MOD -GM)	MAE	RMSD	Bias (MOD -GM)	MAE	RMSD
AR	688	-0.30	2.78	3.92	0.11	2.53	3.71	-0.77	3.07	4.15	-0.10	2.67	3.66	-0.52	2.90	4.18
HZZ	485	-0.51	2.29	3.06	0.55	1.93	2.47	-1.59	2.66	3.57	-1.11	1.86	2.67	0.25	2.82	3.49
DYKGT	251	1.95	3.26	4.34	1.73	3.07	4.36	2.22	3.49	4.33	-0.66	1.52	2.21	4.82	5.17	5.85
YK	686	-0.06	2.64	3.51	0.41	2.20	3.05	-0.54	3.10	3.92	-0.79	2.13	2.95	0.63	3.13	3.96

*MOD: MODIS LSTs; GM: ground-measured LSTs; MAE: mean absolute error; RMSD: root mean square deviation;

However, the accuracy at DYKGT station is close to the well-known accuracy of satellite LST products (3-4K). The analysis of the four stations indicates that 1×1km pixel in the DYKGT have been covered by not only the forest but also flood land, grass land and the scrubs between them. While the observation in the station just focuses on the forest canopy. That is the reason why large difference existed between MODIS land surface temperature and the station observation in DYKGT station, and the difference became larger with increasing temperature. The other three stations all located at the broad and plain uniformity place. Therefore, the validation results of the other three stations better represented the accuracy of MODIS LST. All the ground observation data are slightly lower than the MODIS LST except for DYKFT. 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. Therefore the underestimation of MODIS LSTs may caused by the overestimation of the emissivities in retrieving process of MODIS LST.

Comparing with LST observed at station, MODIS LST of Terra has higher accuracy than that of Aqua. The bias, MAE and RSMD of Terra are lower than Aqua (Table 2). The difference of LST products between the two satellites is mainly resulted from the difference between the two remote sensing instruments. Nighttime MODIS LST products are closer to LST observed at station than daytime MODIS LST products. That is attributed to the direction of solar radiation in daytime, and the pixel is mixture of shadow and light. What's more the maximum observation angle of MODIS is 65 degree from nadir, while the longwave radiation is observed vertically at the four stations. All those aspects contribute to difference between the MODIS LST and ground measurement LST. These can be ignored in nighttime for no solar radiation affection. Thus the validation in the nighttime does not need to consider it.

5 CONCULSIONS AND DISCUSSIONS

5.1 Conclusions

The longwave radiation ground measurements were successfully used to validate the MODIS LST in Heihe River Basin firstly. The following conclusions can be obtained:

(1) The three typical stations validation results indicated that the MODIS Land surface temperature can match well with the ground measurements with bias<0.5K, MAE<3, RMSD between 3K and 4K., and MODIS LST products are underestimated.
(2) From the results, the LST accuracy of MODIS based on the Terra is lower than that based on the Aqua.
(3) The difference between MODIS LSTs and ground measurements in nighttime is smaller than that in the daytime.

5.2 Discussions

Ground measurements are discrete in space, while satellite-derived LSTs are discrete in time. Thus the scale mismatch issue in both space and time must be considered firstly. Ground measured LSTs were only available over one fixed point in each station. The small footprint of the ground sensors, mostly about 30 meter, may not represent the spatial variation in the MODIS footprint, for example the DYKGT site. However, footprint of observation in validation stations (such as YK station, AR station, HZZ station) can represent the variation among the canopies if the canopy is homogeneous. Moreover, the temporal averaging of ground measurements can harmonize the two different types of data and further mitigate the scale mismatch issue[21].Another concern is that the ten minutes average ground measurements may not represent the LST at the time of the satellite overpass. LST changes slowly in ten minutes if there are no clouds. The MODIS LST values affected by cloud have been filter according to MOD11_L2QC information and manual examination. In this study, only clear sky observations were used to be validated MODIS LST. Therefore, the effect of clouds in ground measurements should be small, and ground measurements can represent the LST at the time of satellite overpass.

Two assumptions about broadband emissivities were made in calculating the ground-measured land surface temperature: (1)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. (2) Emissivity is assumed constant over time. These assumptions are based on below issues.

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 [22]. Surface emissivity affected by vegetation density and other factors such as precipitation and snow cover, which change frequently over time. Therefore it is very difficult to obtain accurate emissivity for so much validation data under a wide variety of surface conditions without conducting ground measurements.

Over cropland and grassland sites at high latitude, the second 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 green vegetation. Stations covered by vegetation often have higher emissivities during growing season. However, the temporal averaging emissivity of the whole growing seasons is close to the ASTER in these stations. Therefore the effect of the biases can be ignored in vegetation covered stations.

The ground measurements of surface emissivity are not available in this study. In order to reduce the error caused by the assumption, only the data during the growing season was validated at station with vegetation cover. Therefore, the biases did not include errors due to the uncertainty in surface emissivity. The emissivity values used were more representative of the real ground values during growing season.

Although using longwave radiation measurements of four stations to validate MODIS LST in the Heihe River Basin, there are many field work must be done to obtain more longwave radiation data and ground measured emissivities to validate the MODIS LST sufficiently. Moreover, it is needed to quantify the error caused by the difference view angle between ground station longwave radiation observation equipment and MODIS onboard satellites through field angle experiments.

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REFERENCES

[1] Liang, S., L., "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 (2001).

[2] Peres, L., F. and DaCamara, C., C., "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 (2004).

[3] Wan, Z., “MODIS Land-Surface Temperature Algorithm Theoretical Basis Document (LST ATBD), Version 3.3,”University of California (1999).

[4] Wan, Z., M. and Li, Z. L., "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 (1997).

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

[6] Greenbelt, “Earth Observing System ClearingHOuse (ECHO) / Warehouse Inventory Search Tool (WIST) Version 10.X [online application].” MD: Earth Observing System Data and Information System (EOSDIS), Goddard Space Flight Center (GSFC) National Aeronautics and Space Administration (NASA), (2009).

[7] CEOS, WMO, "Revision of AOPC requirements in WMO/CEOS database, "Submitted by the Secretariat, 4pp(2010)

[8] WMO, GCOS-107, "Systematic Observation Requirements for Satellite-based Products for Climate," WMO TD, 1338, 90 (2006).

[9] Coll, C., Caselles, V., Galve, J., M., Valor, E., Niclòs, R., Sánchez, J., M. and M., Rivas, R.., "Ground measurements for the validation of land surface temperatures derived from AATSR and MODIS data, " Remote

Sensing of Environment, 97(3), 288-300 (2005).
[10] Menzel, W., P., Seemann, S., W., Li, J. and Gumley, L., E., “MODIS atmospheric profile retrieval algorithm theoretical basis document,” University of Wisconsin-Madison, (2002).
[11] Wan, Z., M., Zhang, Y., Zhang, Q. and Li, Z., L., "Quality assessment and validation of the MODIS global land surface temperature," International Journal of Remote Sensing, 25(1), 261-274 (2004).
[12] Wan, Z., M., Wang, P., and Li, X., "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 (2004).
[13] Wan, Z., M., Zhang, Y., Zhang, Q., and Li, Z., L., "Validation of the land surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data," Remote Sensing of Environment, 83(1-2), 163-180 (2002).
[14] Wang, K., C. and Liang, S., L., "Evaluation of ASTER and MODIS land surface temperature and emissivity products using long-term surface long-wave radiation observation at SURFRSD sites," Remote Sensing of Environment, 113(7), 1556-1565 (2009).
[15] Wang, K., C., Wan, Z., M., Wang, P., C., Sparrow, M., Liu, J., M., "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), 1-12 (2005).
[16] Wang, W., H., Liang, S., L. and Meyers, T., "Validation MODIS land surface temperature products using long-term nighttime ground measurements," Remote Sensing of Environment, 112, 623-635 (2008).
[17] Li, X., Li X., W., Li, Z., Y., Ma, M., G., Wang, J., Xiao, Q., Liu, Q., Che, T., Chen, E., X., Yan, G., J., Hu, Z., Y., Zhang, L., X., Chu, R., Z., Su, P., X., Liu, Q., .H., Liu, S., M., Wang, J., D., Niu, Z., Chen, Y., Jin, R., Wang, W., Z., Ran, Y., H., Xin, X., Z. and Ren, H., Z., "Watershed Allied Telemetry Experimental Research, " Journal of Geophysical Research, 114(D22103), doi: 10.1029/ 2008JD011590 (2009).
[18] http://speclib.jpl.nasa.gov/.
[19] Baldridge, A., M., Hook, S., J., Grove, C., I. and Rivera, G., "The ASTER Spectral Library Version 2.0," Remote Sensing of Environment, 113, 711-715(2009).
[20] Liang, S., L., "Quantitative remote sensing of land surfaces, "In J. A. Kong (Ed.) & Wiley series in remote sensing, John Wiley & Sons (2004).
[21] Schmetz, J., "Towards a surface radiation climatology: Retrieval of downward irradiances from satellites," Atmospheric Research, 23(3-4), 287-321(1989).
[22] vande Griend, A., A. and Owe, M., "On the relationship between thermal emissivity and the normalized difference vegetation index for natural surfaces, " International Journal of Remote Sensing, 14(6),1119-1131 (1993).