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Land Surface Temperature Measurements
from EOS MODIS Data

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As part of the efforts in the evaluation and validation of the MODIS Land-Surface Temperature (LST) product, two case studies have been made to demonstrate the applications of the MODIS LST product in regional and global change studies. A comparison of the LSTs in the part of North America including the contiguous United States in the last two winters confirmed earlier National Oceanic and Atmospheric Administration (NOAA) reports that the United States was unusually warm and dry during the 2001-02 winter (December 2001 through February 2002). The MODIS LST difference is corroborated with its high correlation to the difference in statewide mean surface air temperatures based on weather station data. The MODIS LST product is also used in a case study for monitoring thermal status of ecosystems with MODIS LST and vegetation index products.

Eight thermal infrared radiometers have been deployed since late June 2002 in a soybean field and a rice field in the middle of State of Mississippi in order to validate the MODIS LST product in wet atmospheric conditions.

The noise equivalent temperature difference (NEDT) and the calibration accuracy of the early Aqua MODIS thermal infrared data were estimated by comparing the Terra and Aqua MODIS data over the high-elevation Lake Titicaca, Bolivia on June 26, 2002.

New refinements and improvements were made to the MODIS LST code for improving the quality of the MODIS LST product. The MODIS LST code has been updated for the combined use of Terra and Aqua MODIS data in simultaneous retrieval of the land-surface temperatures and emissivities.

Recent Papers

- Z. Wan, Estimate of noise and systematic error in early thermal infrared data of the Moderate Resolution Imaging Spectroradiometer (MODIS), *Remote Sens. Environ.*, Vol. 80, pp. 47-54, 2002.
- Z. Wan, Y. Zhang, Z.-L. Li, R. Wang, V.V. Salomonson, A. Yves, R. Bosseno, and J. F. Hanocq, Preliminary estimate of calibration of the Moderate Resolution Imaging Spectroradiometer (MODIS) thermal infrared data using Lake Titicaca, *Remote Sens. Environ.*, Vol. 80, pp. 497-515, 2002.
- X.-L. Ma, Z. Wan, C.C. Moeller, W.P. Menzel, and L.E. Gumley, Simultaneous retrieval of atmospheric profiles, land-surface temperature and emissivity from Moderate Resolution Imaging Spectroradiometer thermal infrared data: extension of a two-step physical algorithm, *Applied Optics*, Vol. 41, pp. 909-924, 2002.
- Z. Wan, Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data, *Remote Sens. Environ.*, in press 2002.

1. INTRODUCTION

Land-surface temperature (LST) is one of the key parameters in the physics of land-surface processes on regional and global scales, combining the results of all surface-atmosphere interactions and energy fluxes between the atmosphere and the ground (Mannstein, 1987; Sellers et al., 1988). One of the most important potential applications of the LST retrieved from satellite data is to validate and improve the global meteorological model prediction after appropriate aggregation and parameterization (Price, 1982; Diak and Whipple, 1993). Besides its necessity in the LST retrieval, the surface emissivity can be used to discriminate senescent vegetation (French et al., 2000a). 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, in estimation and parameterization of surface fluxes (Brutsaert et al., 1993; French et al., 2000b), and in estimate the diurnal cycle (Jin and Dickinson, 1999). LST can be also used to monitor droughtiness and estimate surface soil moisture (Feldhake et al., 1996; McVicar and Jupp, 1998), to evaluate water requirements of wheat (Jackson et al., 1977) and to determine frosts in orange groves (Caselles and Sobrino, 1989).

The MODIS (Salomonson et al., 1989) onboard the first EOS platform (called Terra), that was successfully launched on 18 December 1999, provides a new opportunity for global studies of atmosphere, land, and ocean processes (King et al., 1992; Justice et al., 1998; Esaias et al., 1998), and for satellite measurements of global LST. The strengths of MODIS include its global coverage, high radiometric resolution and dynamic ranges suitable for atmosphere, land, or ocean studies, and accurate calibration in multiple TIR bands designed for retrievals of sea surface temperature (SST), LST and atmospheric properties. Specifically, band 26 will be used to detect cirrus clouds (Gao and Kaufman, 1995), band 21 for fire detection (Kaufman et al., 1998), all other TIR channels will be used to retrieve atmospheric temperature and water vapor profiles (Smith et al., 1985). TIR bands 20, 22, 23, 29, 31-33 will correct atmospheric effects and retrieve surface emissivity and temperature (Wan and Li, 1997). This report will present two case studies to demonstrate the applications of the MODIS LST product in regional and global change studies, recent validation activities, estimate of the NEDT and calibration accuracy of the early Aqua MODIS thermal infrared data, and new refinements and improvements to the MODIS LST code for improving the quality of the MODIS LST product.

2. EXAMPLES OF APPLICATIONS OF THE MODIS LST PRODUCT

2.1 Case Study 1

Since the reprocessing of MODIS LST products for data day beginning 1 November 2000, we have had consistent MODIS LST products (collection 3) for more than 16 months. Therefore, it may be possible to get some insights into the applications of the MODIS LST products. The 16 months of MODIS LST products cover two winters. According to National Oceanic and Atmospheric Administration (NOAA)

reports in <http://www.noaanews.noaa.gov/stories/s599.htm> and [s869.htm](http://www.noaanews.noaa.gov/stories/s869.htm), the winter of 2000-2001 (December 2000 through February 2001) was cooler than normal in the contiguous United States, and this region experienced record warmth during the three-month period from November 2001 to January 2002.

As part of the efforts in the evaluation and validation of the MODIS LST product, we compared the LSTs in the contiguous United States in the last two winters. The monthly composite/average daytime LSTs in the part of North America including the contiguous United States in Winter 2002 (December 2001 through February 2002) are shown in Fig. 1 (in the sequence from left to right). We can see that the cold surface temperatures below the freezing point (0°C) existed only in the Rocky Mountains area, and that February 2002 was warmer than January 2002. These features were consistent with the MODIS snow observations: snow was late to arrive and early to recede in many parts of the U.S. (refer to <http://earthobservatory.nasa.gov/Newsroom/Winter2002/> for the MODIS snow maps). After taking average of the monthly composite/average LSTs in December 2000 through February 2001 (not shown) and in December 2001 through February 2002, we get the averaged LSTs in Winter 2001 and Winter 2002. The LST differences between Winter 2002 and Winter 2001 are shown in Fig. 2 with the daytime LST difference on the left side and the nighttime one on the right. It is obviously that both the daytime and nighttime LSTs were warmer in Winter 2002 by a few degrees up to more than 10°C over the vast areas from Rockies eastward, and that they were cooler by a few degrees in the Rocky Mountains area.

It should be pointed out that there are intrinsic differences between the conventional surface temperatures measured at weather stations and the LSTs from MODIS observations. The former is the air temperature measured by thermometers 2 meters above the ground hourly or once every half hours in all weather conditions. However, MODIS measures the thermal radiation emitted from the planet's land-ocean-atmospheric system at its specific overpass time. Over the land, it is the surface-whether it is bare ground, vegetation canopy, lakes or rooftops that emit the thermal radiation. It is possible to make accurate atmospheric corrections to retrieve the land-surface temperature only in clear-sky conditions from the MODIS thermal radiance data collected around 10:30am and 10:30pm local solar time. Simultaneous measurements of the surface air temperature with thermistors and the land-surface temperature with thermal radiometers after correcting the effects of surface emissivity and surface reflected atmospheric thermal radiation indicate that the difference between the land-surface temperature and the surface air temperature varies with land-cover materials and structures, solar zenith angle, wind speed, and the viewing angle of the land-surface temperature. The difference may be as large as 15°C over soils or several degrees over crops in daytime, and in general it is small at night in both cases.

Although it seems meaningless to make direct comparison of the land-surface temperature with surface air temperature because of their intrinsic differences mentioned above, they are still highly correlated, i.e. a higher land-surface temperature generally corresponds to a higher surface air temperature at the same location. Because of their differences and correlation, land-surface temperature and surface air

temperature are both useful in various applications. For example, with the temporal series of air temperature around crops and the temperature of the crops, farmers can better estimate water requirements and productivity. It will be a challenge to apply the two kinds of surface temperatures into applications appropriately. A major advantage of the LST from satellite observations is its global coverage. MODIS measures the temperature of nearly every square kilometer of the Earth's surface roughly twice a day and more frequently in high latitude regions. Satellite observations are the only means to measure the LST in remote areas where there are a few weather stations if any.

It is believed that there is an even stronger correlation between the surface air temperature difference and the land-surface temperature difference over the same period of time in the same region because regional warming and cooling should have similar effects on these two kinds of temperatures. Fortunately, the statewide mean (surface air) temperature data are already available from the web site <http://lwf.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html> for all the months in the last two winters so we can compare the surface air temperature difference with the LST differences shown in Fig. 2. Table I shows the monthly statewide mean surface air temperatures in seven states of the northern Great Plains where warm temperatures dominated Winter 2002 with the LST difference larger than 5 °C, and one state (Utah) in the Rocky Mountains area where the LST was cooler in Winter 2002. The geolocations of the United States are shown in Fig. 3. The monthly mean surface air temperatures are given in columns 2-4 and 7-9 of Table I for each of the eight states. The winter average surface air temperatures are given in columns 5-6 and 10-11 in unit of °F and °C, respectively. The winter air temperature differences are given in the last column. In the northern Great Plains states, the winter air temperature difference varied from 7.67 °C in Iowa to 4.58 °C in Michigan. It was -2.04 °C in Utah. We can see the high correlation between these numbers and the LST difference colors of the corresponding states in Fig. 2, and believe that the LST differences can be justified further because of the following reasons: (1) while all weather conditions are considered in the mean air temperature, the LSTs are only for clear-sky conditions so that it is reasonable to have larger LST differences than the air temperature differences; (2) after considering the spatial variation of a few or several °C in the air temperature within large states (this can be confirmed with air temperature data station by station but the detailed air temperature data are not available on web sites yet), the winter air temperature difference could be larger than 10 °C in the warm spots in Iowa where the daytime LST differences were around 13 °C.

The close correlation among the monthly LSTs in Fig. 1 and the high correlation between the surface air temperature differences in Table I and the LST differences in Fig. 2 may be considered as the corroboration of the MODIS LST product over a long period of time on a large regional scale. Because we do not have the resources and the time to conduct ground-based measurements to validate the MODIS LST product on large regional scales, we have to depend on indirect validations with regional and global events such as in this case study. We need to evaluate the quality of the MODIS LST product through its regional and global applications. Once the MODIS LST product is available for a continuous period of 5-10 years, it

will be possible to find the global or regional mean LST values and to study the seasonal and annual variations in the LSTs for various applications.

2.2 Case Study 2

The MODIS LST and normalized difference vegetation index (NDVI) products were used in a global study for monitoring thermal status of ecosystems. The yearly peak values of NDVI data at 5km grids were used to define six NDVI peak zones from -0.2 to 1 in steps of 0.2, and the monthly NDVI values at each grid were sorted in decreasing order, resulting in 12 layers of NDVI images for each of the NDVI peak zones. The mean and standard deviation of daytime LSTs and day-night LST differences at the grids corresponding to the first layer of NDVI images characterize the thermal status of terrestrial ecosystems in the NDVI peak zones. For the ecosystems in the 0.8-1 NDVI peak zone, daytime LSTs distribute from 0-35 °C and day-night LST differences distribute from -2 to 22 °C. The daytime LSTs and day-night LST differences corresponding to the remaining layers of NDVI images show that the growth of vegetation are limited at low and high LSTs. LSTs and NDVI may be used to monitor photosynthetic activity and drought, as shown in their applications to a flood-irrigated grassland in California and an unirrigated grassland in Nevada. Detailed results of this study are given in the appendix.

3. NEW VALIDATION ACTIVITIES

We conducted eight field campaigns in 2000 and 2001 at validation sites including lakes, playa, grasslands, snow, and rice fields in California and Nevada. The MODIS LST products were validated within 1K with in situ radiometer measurements in 19 clear-sky cases in the LST range from 263K to 322K and the atmospheric column water vapor range from 0.4 to 3.0cm (Wan et al., 2002).

In order to validate the MODIS LST product in wet atmospheric conditions, we need to find some large croplands in southern mid states where the column water vapor is larger than 4cm in the summer. After a field investigation in the states of Arkansas, Tennessee, Louisiana, and Mississippi in early March of 2002, we found a rice field and a soybean field in Greenville, Mississippi. The size of the rice field is larger than 1km by 1km, and it is surrounded by soybean fields. The soybean field is even larger and it is surrounded by other agricultural lands. In late June 2002, we deployed three thermal infrared radiometers in the rice field and five in the soybean field. The MODIS LST values over the test sites will be compared with in situ measurement data collected in clear-sky conditions. The comparison results will be presented in the next semi-annual report.

4. EVALUATION OF THE EARLY AQUA MODIS TIR DATA

The noise equivalent temperature difference (NEDT) and the calibration accuracy of the early Aqua MODIS thermal infrared data were estimated by comparing the Terra and Aqua MODIS data over the

high-elevation Lake Titicaca, Bolivia on June 26, 2002. The Terra overpassed the lake around 3AM UTC and the Aqua overpassed the lake three hours later. The calibrated radiance granule IDs of the Terra MODIS and Aqua MODIS are MOD021KM.A2002177.0300 and MYD021KM.A2002177.0600, respectively.

With the same approach used in Wan (2002), a sub area of 10 lines by 16 pixels was searched for smallest standard deviation in the brightness temperatures in band 31 in the Terra and Aqua MODIS calibrated radiance data in Lake Titicaca. The standard deviation values in brightness temperatures in all TIR bands are used as the estimated NEDT values. They are shown in columns 5 and 7 in Table II.

The estimated calibration bias values of the Terra MODIS TIR bands, shown in column 6 of Table II, are based on in situ measurements in Lake Titicaca in June 2001 (Wan et al., 2002). If we ignore the small change in lake surface temperature and the effect of changes in atmospheric conditions during the three hours, we can use the average of the brightness temperatures in the sub area to estimate the Aqua MODIS calibration bias in bands 20-23, 29, 31-32. Note that the new radiance product file (MYD021KM.A2002177.0600.V3.1.0.2.hdf) based on the onboard calibration coefficients was used to update the preliminary estimate with the old file based on preflight calibration coefficients. The values of the newly estimated calibration bias are listed in the last column of Table II. Note that the values before parentheses are based on the brightness temperatures converted from Aqua MODIS radiance values with the relative spectral response (RSR) functions of the Aqua MODIS instrument, and the values in parentheses are based on the brightness temperatures converted from radiance values with the RSR functions of the Terra MODIS instrument. The difference in the brightness temperatures due to difference RSR functions is larger than 0.1K in bands 20 and 29.

The above estimates of the NEDT and calibration accuracy of the early Aqua MODIS TIR data indicate that the Aqua MODIS instrument met or nearl met the specifications in the TIR bands 20, 22-23, 29, and 31-32, that are critical for the LST/emissivity retrieval.

5. NEW IMPROVEMENTS OF THE MODIS LST ALGORITHM

We made the following new improvements in the updated MODIS LST code (version 4).

The current version of the MODIS LST code only process land pixels in clear-sky conditions at the confidence of 99% defined by the MODIS cloud-mask product (MOD35). This results in lake pixels without LST value in many situations. It is not likely that there are clouds only over lakes while all the surrounding land pixels are in clear-sky conditions. Per suggestions from Simon Hook of JPL and others, we changed the code so that lake pixels in clear-sky at a confidence of 66% and higher are also processed. This modification improves the continuity in the LST images across lakes and surrounding lands.

In the day/night LST algorithm, there is a variable of BRDF shape factor, also called anisotropic factor, that describes the ratio of the surface-reflected solar beam in MODIS bands 20, 22, and 23 in the spectral range of 3.5-4.2 μm to the radiance that would have resulted if the surface reflected isotropically. Because only one pair of daytime and nighttime MODIS observations is used in the day/night LST algorithm, there is not enough information to accurately determine this BRDF shape factor. The BRDF parameters in the MODIS BRDF/Albedo product (MOD43B1C) are retrieved from visible and near-infrared MODIS data in multiple days. The spectral center of band 7 is at 2.13 μm , not far from the spectral range of 3.5-4.2 μm where MODIS bands 20, 22, and 23 are located. The BRDF parameters depend on the optical properties of surface materials and the structure of the surface. Because terrestrial materials have compatible reflectance values in the spectral range from 2 μm to 4.2 μm (Salisbury et al., 1991), it is reasonable to assume that the BRDF shape does not significantly change in this spectral range. Therefore, we changed the LST code so that it uses the BRDF parameters in band 7 in the MODIS BRDF/Albedo product (MOD43B1C) as inputs to determine the initial guess value of the BRDF shape factor in bands 20, 22, and 23.

In the current version of the MODIS LST code, the range of viewing zenith angle of the MODIS observations is separated into four sub-ranges (i.e., 0-40, 40-52, 52-60, and 60-65 degrees). We only keep one set of MODIS data in seven bands for daytime and nighttime observations in each sub-range, respectively, in the interim files that are used by the day/night LST algorithm. In order to keep more data in the viewing angle range of 0-40 degrees, we changed the 4 sub-ranges to 5 sub-ranges (i.e., 0-24, 24-38, 38-49, 49-58, and 58-65 degrees).

We also improved the LST code by adding a capability of parallel processing for data of odd days and even days so that the production rate may be doubled.

A split-window method is incorporated into the day/night algorithm to ensure that the retrieved emissivities can be used by split-window algorithms.

We changed the LST code so that the Terra and Aqua MODIS data may be used jointly in the day/night LST algorithm to improve the quality of the LST/emissivity product because of better spatial and angular coverages of the MODIS data.

6. WORK PLAN

The in situ measurements with TIR radiometers in the rice and soybean fields in Mississippi will be continued to the end of August. The MODIS LST values over these sites will be compared with in situ measurement data collected in clear-sky conditions for the validation of the LST product in wet atmospheric conditions.

A field campaign will be conducted in mid August and MAS (MODIS Airborne Simulator) flights have been scheduled. In situ measurements will be made with TIR radiometers in Walker Lake, Nevada in order to evaluate the calibration accuracy of Aqua MODIS thermal infrared data.

Tests will be made to use Terra and Aqua MODIS data jointly in the LST code and to evaluate the effect on the improvements in the LST product.

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TABLE I. Comparison of the averaged statewide mean surface air temperatures in the last two winters based on the data in <http://lwf.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html>

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(11)-(6)
state	mean temperature (°F)			winter average		mean temperature (°F)			winter average		winter difference
	Dec00	Jan01	Feb01	(°F)	(°C)	Dec01	Jan02	Feb02	(°F)	(°C)	(°C)
Iowa	10.0	20.8	18.0	16.3	-8.74	30.8	29.1	30.3	30.1	-1.07	7.67
Minnesota	3.0	16.3	7.0	8.8	-12.91	22.7	19.4	24.3	22.1	-5.48	7.43
Wisconsin	9.1	19.5	15.0	14.5	-9.72	27.8	24.9	26.7	26.5	-3.07	6.65
S. Dakota	10.7	22.6	12.4	15.2	-9.31	24.7	24.7	30.0	26.5	-3.07	6.24
Illinois	17.6	25.6	30.8	24.7	-4.07	35.8	34.8	35.5	35.4	1.87	5.94
Indiana	19.3	27.1	33.5	26.6	-2.98	37.2	34.6	34.8	35.5	1.96	4.94
Michigan	16.5	23.8	22.4	20.9	-6.17	32.3	27.9	27.2	29.1	-1.59	4.58
Utah	30.3	26.2	32.7	29.7	-1.26	24.6	25.6	28.0	26.1	-3.30	-2.04

TABLE II. Specifications and estimated performances of the Terra and Aqua MODIS TIR bands.

band	bandwidth (μm)	IFOV	MODIS	Terra MODIS		Aqua MODIS	
			NEDT specified (K)	NEDT estimated (K)	calibration bias estimated (K) (Wan et al., 2002)	NEDT estimated (K)	calibration bias estimated (K)
20	3.660-3.840	1km	0.05	0.09	0.60	0.07	0.37 (0.13)
21	3.929-3.989	1km	2.00	0.85	0.46	1.89	
22	3.929-3.989	1km	0.07	0.16	0.55	0.06	0.27 (0.28)
23	4.020-4.080	1km	0.07	0.17	0.40	0.11	0.25 (0.31)
24	4.433-4.498	1km	0.25	0.28		0.18	
25	4.482-4.549	1km	0.25	0.22		0.18	
27	6.535-6.895	1km	0.25	0.42		0.21	
28	7.175-7.475	1km	0.25	0.60		0.14	
29	8.400-8.700	1km	0.05	0.13	0.03	0.09	0.46 (0.61)
30	9.580-9.880	1km	0.25	0.35		0.21	
31	10.780-11.280	1km	0.05	0.05	0.12	0.05	0.12 (0.12)
32	11.770-12.270	1km	0.05	0.07	-0.14	0.07	-0.11 (-0.11)
33	13.185-13.485	1km	0.25	0.36	0.55	0.11	
34	13.485-13.785	1km	0.25	0.31		0.14	
35	13.785-14.085	1km	0.25	0.27		0.16	
36	14.085-14.385	1km	0.35	0.53		0.22	

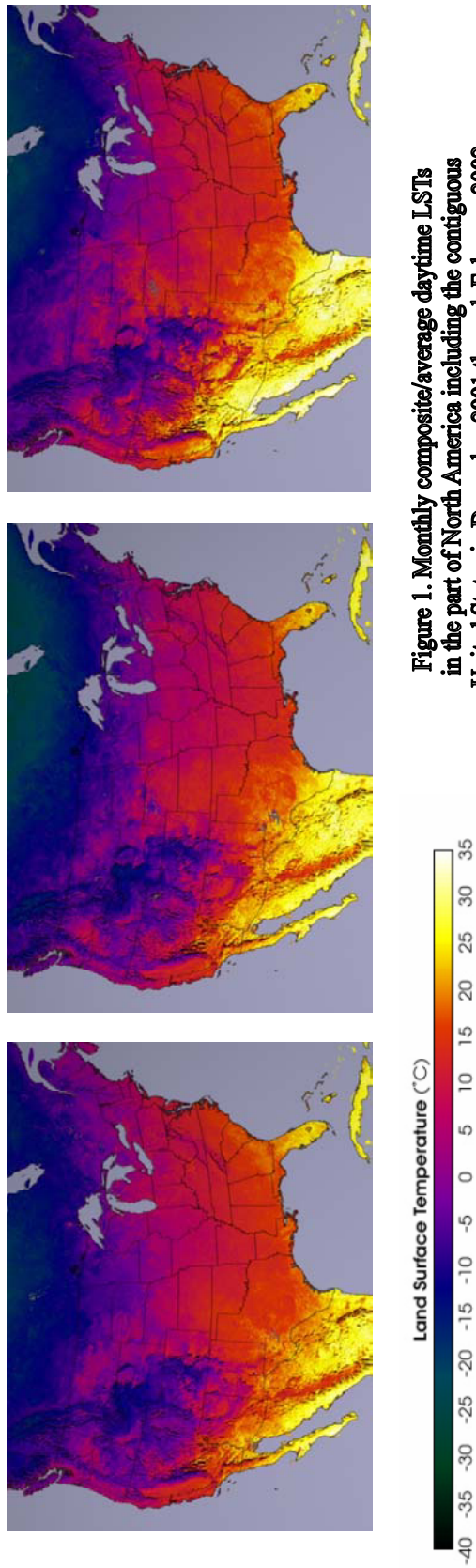


Figure 1. Monthly composite/average daytime LSTs in the part of North America including the contiguous United States in December 2001 through February 2002 (from left to right).

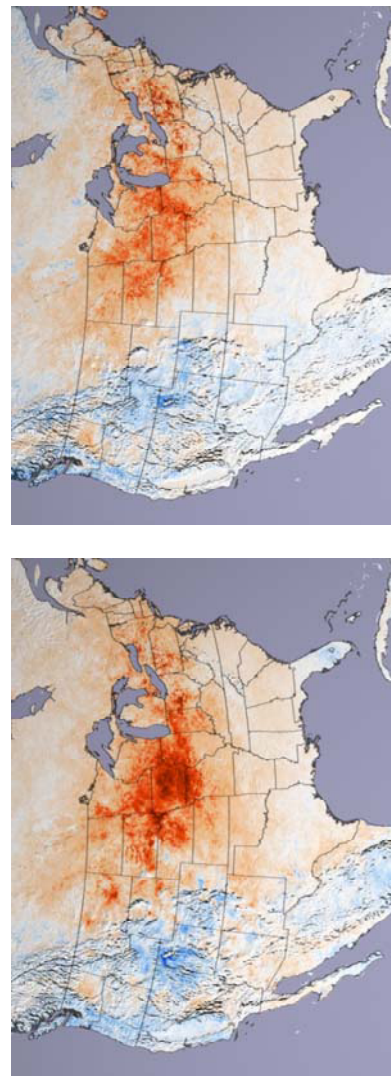


Figure 2. The difference in daytime LST (left) and nighttime LST (right) between Winter 2002 and Winter 2001.



Figure 3. Geolocations of the United States.

Appendix

Monitoring thermal status of ecosystems with MODIS land-surface temperature and vegetation index products

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ABSTRACT

The global land-surface temperature (LST) and normalized difference vegetation index (NDVI) products retrieved from Moderate Resolution Imaging Spectroradiometer (MODIS) data in 2001 were used in this study. The yearly peak values of NDVI data at 5km grids were used to define six NDVI peak zones from -0.2 to 1 in steps of 0.2, and the monthly NDVI values at each grid were sorted in decreasing order, resulting in 12 layers of NDVI images for each of the NDVI peak zones. The mean and standard deviation of daytime LSTs and day-night LST differences at the grids corresponding to the first layer of NDVI images characterize the thermal status of terrestrial ecosystems in the NDVI peak zones. For the ecosystems in the 0.8-1 NDVI peak zone, daytime LSTs distribute from 0-35 °C and day-night LST differences distribute from -2 to 22 °C. The daytime LSTs and day-night LST differences corresponding to the remaining layers of NDVI images show that the growth of vegetation is limited at low and high LSTs. LSTs and NDVI may be used to monitor photosynthetic activity and drought, as shown in their applications to a flood-irrigated grassland in California and an unirrigated grassland in Nevada.

Keywords: MODIS, land-surface temperature, NDVI, ecosystem, photosynthetic activity, drought

1. INTRODUCTION

As a part of the NASA-centered international Earth Observing System (EOS), two MODIS instruments¹ have been launched to provide information for global studies of atmosphere, land, and ocean processes. The first one was launched 18 December 1999 on the morning platform called Terra, and the second one was launched 4 May 2002 on the afternoon platform called Aqua. The strengths of MODIS 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 (in 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.

NDVI and LST are two of the MODIS land product suite.² The MODIS VI products have been designed for seasonal and interannual monitoring of the Earth's vegetation. The NDVI product maintains continuity with the NDVI data record from the Advanced Very High Resolution Radiometers (AVHRR).^{3, 4} Vegetation indices have been used to conduct land cover classifications,⁵ and derive biophysical properties of the vegetation such as fractional vegetation cover, biomass, leaf area index, fraction of absorbed photosynthetic active radiation and phenology.^{6, 7, 8}

LST is one of the key parameters in the physics of land-surface processes on regional and global scales, combining the results of all surface-atmosphere interactions and energy fluxes between the atmosphere and the ground.^{9, 10} The remotely sensed LST has been used in land cover and land-cover change analysis,^{11, 12} and in the production of the MODIS land cover product. It has also been used in monitoring drought and estimating surface soil moisture,^{13, 14} evaluating water requirements of wheat,¹⁵ and determining frosts in orange groves.¹⁶

The level-2 MODIS LST product (MOD11_L2) is retrieved with the generalized split-window LST algorithm¹⁷ from the calibrated radiance data of bands 31 and 32 data in the MODIS Level-1B 1km resolution (MOD021KM) product. Other inputs to this algorithm include MODIS geolocation product (MOD03), cloudmask product (MOD35), and atmospheric temperature and water vapor profile product (MOD07). The emissivities in bands 31 and 32 are estimated from land cover types¹⁸ in the MODIS land-cover product (MOD12Q) and snow cover product (MOD10) through look-up tables established by TIR BRDF (bidirectional reflectance distribution function) and emissivity modeling.¹⁹ The 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. To resolve this problem, a physics-based day/night algorithm²⁰ was developed to retrieve surface spectral emissivity and temperature at 5km resolution for the MODIS LST level-3 MOD11B1 product from a pair of daytime and nighttime MODIS data in seven TIR bands, i.e., bands 20, 22, 23, 29, and 31-33. The accuracy of daily MODIS LST product has been validated in nineteen clear-sky cases with in-situ measurement data collected in field campaigns in 2000 and 2001. The MODIS LST accuracy is better than 1K in the range from 263K to 322K over Lake Titicaca in Bolivia, Mono Lake, Bridgeport grassland, and a rice field in Chico, California, Walker Lake and a silt playa in Railroad Valley, Nevada, in the atmospheric column water vapor range from 0.4 to 3.0cm.²¹ The MODIS LST product was also validated with in-situ TIR radiometer measurements in Lake Tahoe, CA/NV, in 27 clear-sky cases in 2000 and 2001 by Simon Hook, JPL, and it was found that the MODIS LST product has a small bias of 0.12K and the standard deviation of its differences from the in-situ values is 0.3K (personal communications). In mid July 2002, the MODIS LST product was also validated at the same accuracy with in-situ measurements in a soybean field near Greenville, Mississippi, in the atmospheric column water vapor range up to more than 4cm.

This paper presents the early results in monitoring thermal status of ecosystems with the MODIS LST and NDVI products.

2. MODIS DATA PRODUCTS USED IN THIS STUDY

Twelve sets of the 16-day MODIS VI product (MOD13A2) were ordered from the NASA EOS Data Gateway (<http://redhook.gsfc.nasa.gov/~imswwww/pub/imswelcome/>) in order to use the global NDVI data sets for year 2001. The file names and the starting dates of the periods of 16 days are listed in Table 1. There are 281 files in each set of the VI product to cover all the land of the Earth between latitudes 60 °S and 80 °N. The MODIS VI product provides NDVI data at the 1km-resolution grids in the integerized sinusoidal (ISIN) projection. The exact size of the 1km grid is 0.928km by 0.928km. The valid range of the NDVI data is from -2000 to 10000, giving NDVI values in the range of -0.2 to 1.0 after divided by a scale factor of 10000. We mosaiced all the files in each set and aggregated the NDVI data at 1km grids into 5km grids by taking average of all the NDVI data in the valid range. The NDVI values at 5km grids in the mosaic images are stored in 8-bit unsigned integer in the valid range of 0 to 240 with the lower limit 0 corresponding to NDVI value -0.2 and the higher limit 240 corresponding to NDVI value of 1.0. A quantization error of 0.0025 associated with the 8-bit unsigned integer is believed to be smaller than the error and uncertainty of the NDVI data. A fill value of 255 is given for grids in ocean and cloudy conditions. After this processing, we have 12 sets of global NDVI images representing monthly NDVI values in this study for the global except the polar regions.

For the whole year of 2001, the daytime and nighttime LSTs were taken from the daily 5km MODIS LST product (MOD11B1) that is also available from the EOS Data Gateway free of charge. The LST data are stored in 16-bit unsigned integer in the valid range of 7500 to 65535, giving LST values in the range of 150 to 1310.7K after multiplying a scale factor of 0.02 (K). A fill value of 0 is given for grids in ocean and cloudy conditions. We mosaiced the LSTs in 317 tiles of the MOD11B1 product into global LST data set each day. Then the daily global LST sets were composited and averaged to obtain the monthly daytime and nighttime LST data sets for 2001. The exact size of the 5km-resolution grids is 4.64km by 4.64km. One set of global LST data at 5km grids are stored in 4320 rows by 8640 columns. In the MODIS LST processing, only the MODIS data in clear-sky conditions at a confidence of 99% defined by the MODIS cloud-mask product (MOD35) are used to retrieve LST values. It is possible that there is no LST value for some grids that have valid NDVI values because a different definition of clear-sky pixels is used in the NDVI processing. A cirrus cloud may have an effect large enough to prevent LST retrieval at the 1K accuracy, but it is not necessarily so for the NDVI estimation. The overpass time of the MODIS nadir observations is around 10:30am local solar time in the daytime and around 10:30pm local solar time at night. The MODIS observations at off-nadir viewing angles are made before or after the overpass time in term of the local solar time for the spots being observed. After the compositing and averaging in the generation of the monthly LST data, the daytime and nighttime LSTs represent the averaged LST values in clear-sky conditions around 10:30am and 10:30pm local solar time, respectively. The MODIS LSTs represent the kinetic temperature determined by the TIR radiations from the surfaces of all components within the pixel or grid, including vegetation, soil, water body, and whatever being observed by the MODIS instrument.

3. NDVI PEAK ZONE APPROACH

Because of the great diversity in the global ecosystems, the vegetation at the grids in a 16-day or monthly NDVI image may be in different stage of its phenology, some in growing phase and some in drying phase. In order to highlight the NDVI change at the global scale, a NDVI peak zone approach is applied in the following steps: (1) we separate the NDVI valid range into six sub-ranges, i.e., -0.2 to 0, 0 to 0.2, 0.2 to 0.4, 0.4 to 0.6, 0.6 to 0.8, and 0.8 to 1.0; (2) to find the maximum NDVI value in the 12 monthly NDVI images for each grid, assign it to one of the six sub-ranges according to its maximum NDVI value, and keep the month as its first index, after processing all grids, we get six images of NDVI peak zones as shown in Fig. 1, each corresponding to one of the six sub-ranges; (3) for all the grids in each NDVI peak zone, the NDVI values in 12 months are sorted in decreasing order and keep the corresponding months in the index images, resulting in 12 layers of NDVI images for each NDVI peak zone; (4) according to the index images, corresponding 12 layers of daytime and nighttime LST images are constructed for each NDVI peak zone. Fig. 1 shows the spatial distributions of the NDVI in the six NDVI peak zones. The images in (a) for the 0.8 - 1.0 zone, (b) for the 0.6 to 0.8 zone, and (c) for the 0.4 - 0.6 zone, were enhanced with the histogram equalization method for better visualization. As shown in Fig. 1 (a), NDVI peak values larger than 0.8 are distributed in tropical forests in South America and Africa and Far East, east part of the North America, northern parts of Europe and Asian, and the east part of Asian. These areas are neighboring by the 0.8 - 1.0 NDVI peak zone shown in Fig. 1 (b). Semi-arid areas such the mid west of US and the interior of Australia are shown in Fig. 1 (c) and (d). Desert areas are shown in Fig. 1 (e) for the 0 - 0.2 NDVI peak zone. The last zone (-0.2 to 0) is distributed mainly in Greenland.

4. CHARACTERISTICS OF THE THERMAL STATUS OF THE ECOSYSTEMS

From the 12 layers of NDVI and corresponding index images, daytime and nighttime LST images, we calculated the histograms of the NDVI, daytime LSTs and day-night LST differences for the five NDVI peak zones (covering NDVI from 0.0 to 1.0). Fig. 2 shows the histograms in layers 1, 4, and 7. The histograms in layers 1, 4, and 7 are shown in columns 1, 2, and 3, respectively. In layer 4 of the NDVI image, the time difference between the month with NDVI peak and the month with the 4th largest NDVI value in 12 months may be 2-3 months, varying with grids. Similarly, the time difference in layer 7 of the NDVI image may be 3-6 months. Comparing the NDVI histograms in layers 1, 4 and 7 (from left to right in the top row) clearly shows the NDVI changes in the five NDVI peak zones. Comparing the histograms of daytime LSTs in the middle row shows that the daytime LSTs change toward low and high sides as the NDVI reduces. This feature in the histograms of daytime LSTs indicates that the growth of vegetation is limited at low LSTs due to cold weather and insufficient photosynthetically active radiation and at high LSTs due to strong evapotranspiration. From the histograms of the day-night LST differences in the bottom row, we can see that the daynight LST difference becomes slightly larger as the NDVI reduces. Because an increase in the day-night LST difference is related to a reduce in the apparent thermal inertia of the Earth surface in general and the apparent thermal inertia reduces as the soil gets dry^{22, 23}, the day-night LST difference may be used to estimate the soil moisture and monitor drought.

Means and standard deviations of the NDVI, daytime LSTs and day-night LST differences were also calculated. They are given in Table 2, and the number of 5km grids with LSTs is given in the last column. The number of 5km grids with LSTs may be different because there may be some grids without LST values due to persistent clouds in one month in some areas. When using the mean and standard deviation values in Table 2, beware that the shapes of the histograms in Fig. 2 are different from a normal distribution.

Analysis indicates that although there are weak correlations between NDVI and LST they are independent variables of the ecosystems at the global scale.

5. POTENTIAL APPLICATIONS

Now we try to apply MODIS LST and NDVI products in applications for monitoring thermal status of ecosystems, photosynthetic activity and drought. We have conducted field measurements with TIR radiometers in a grassland at 1972m above sea level in Bridgeport, California since 2000. The size of the grasslands in the Bridgeport valley is about 5km by 5km. The grasslands are irrigated during April 15 and September 15 in shadow canals with water originated from snow-melt in the Sierra Nevada just north of Mono Lake, approximately 30km from the valley. This irrigated land is used for cattle grazing during the summer months. For a comparison, we also look at an unirrigated grassland at

1840m above sea level near Ione, Nevada. This grassland is about 5km wide and 15km long on a gentle slope by the west edge of the Toiyabe National Forest, and approximately 160km away from Bridgeport Valley.

Fig. 3 shows the NDVI, daytime LST and day-night LST difference values for the central portions of the flood-irrigated grassland in Bridgeport and the unirrigated grassland in Nevada in the spring and summer months of 2001. These values were taken from 1km MODIS LST and NDVI products. From this figure, we can get the following insights: (1) In the Bridgeport site the dips in the daytime LSTs and the day-night LST differences are caused by irrigation. (2) The NDVI increases when the daytime LSTs are in the range up to 35 °C in the spring and summer months. The NDVI in the irrigated grassland increases until the end of June. But the NDVI in the unirrigated grassland increases only in April and May. (3) The cooler daytime LSTs and smaller day-night LST differences in early July (julian day 188) in both sites indicate that there was a major storm event in the area at least from Bridgeport, CA to Ione, NV. This precipitation made a slight increase in the NDVI over the unirrigated grassland. The smaller day-night LST difference corresponds to the increase in the soil moisture condition in the unirrigated grassland. (4) The NDVI decreases as the daytime LST is above 35 °C. This example shows that MODIS LST and NDVI products can be used to monitor thermal status of the ecosystems, photosynthetic activity and drought.

The NDVI peak zone approach was also applied to latitude zones, for example, in the zone between latitudes 30-45 degree N that covers most of the USA, the Mediterranean region, Mid East, China, and Japan. We got similar NDVI and day-night LST difference histograms as shown in Fig. 2, but the daytime LST is distributed in smaller ranges and the standard deviations are also smaller. This NDVI peak zone approach can also be used in regions so that we can get the vegetation and thermal characteristics of the regional ecosystems.

When multi-year MODIS LST and NDVI products are available in the near future, we can get their annual variations in different ecosystems for better global and regional change studies.

ACKNOWLEDGMENT

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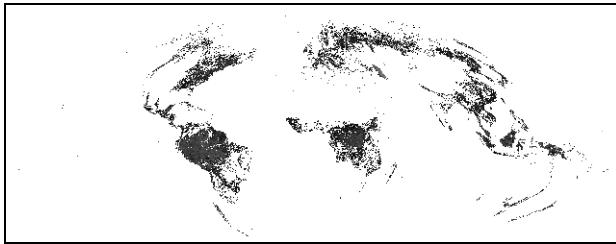
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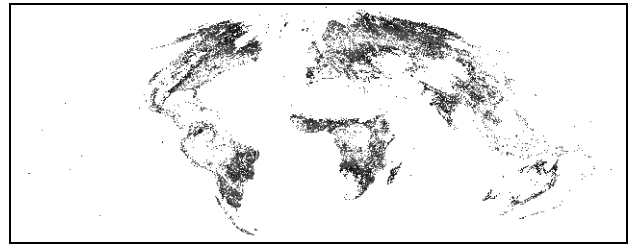
TABLE I. A list of the 16-day NDVI data sets used in this study.

file name	starting date	file name	starting date
MOD13A2.A2001001*.003*.hdf	01/01/2001	MOD13A2.A2001193*.003*.hdf	07/12/2001
MOD13A2.A2001033*.003*.hdf	02/02/2001	MOD13A2.A2001225*.003*.hdf	08/13/2001
MOD13A2.A2001065*.003*.hdf	03/06/2001	MOD13A2.A2001257*.003*.hdf	09/14/2001
MOD13A2.A2001097*.003*.hdf	04/07/2001	MOD13A2.A2001273*.003*.hdf	09/30/2001
MOD13A2.A2001129*.003*.hdf	05/09/2001	MOD13A2.A2001305*.003*.hdf	11/01/2001
MOD13A2.A2001145*.003*.hdf	05/29/2001	MOD13A2.A2001337*.003*.hdf	12/03/2001

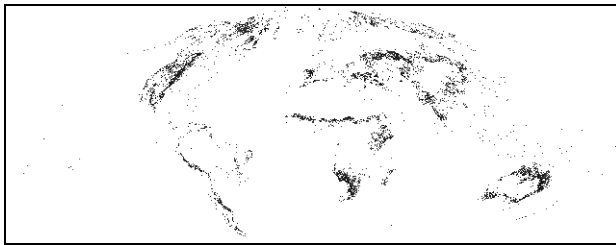
Fig. 1 Spatial distributions of the NDVI in the six NDVI peak zones.
Note that the images in (a) - (c) were enhanced with the histogram equalization method.



(a) 0.8 - 1.0



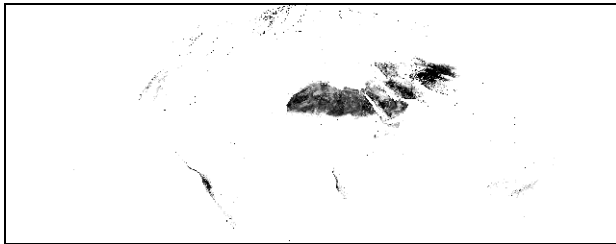
(b) 0.6 - 0.8



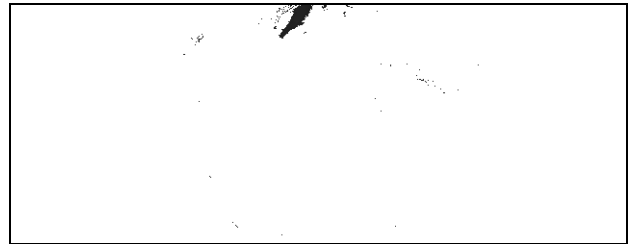
(c) 0.4 - 0.6



(d) 0.2 - 0.4



(e) 0.0 - 0.2



(f) -0.2 - 0.0

Fig. 2, Histograms of the NDVI (a), daytime LST (b), and day-night LST difference (c) in layers 1, 4, and 7 of NDVI images.

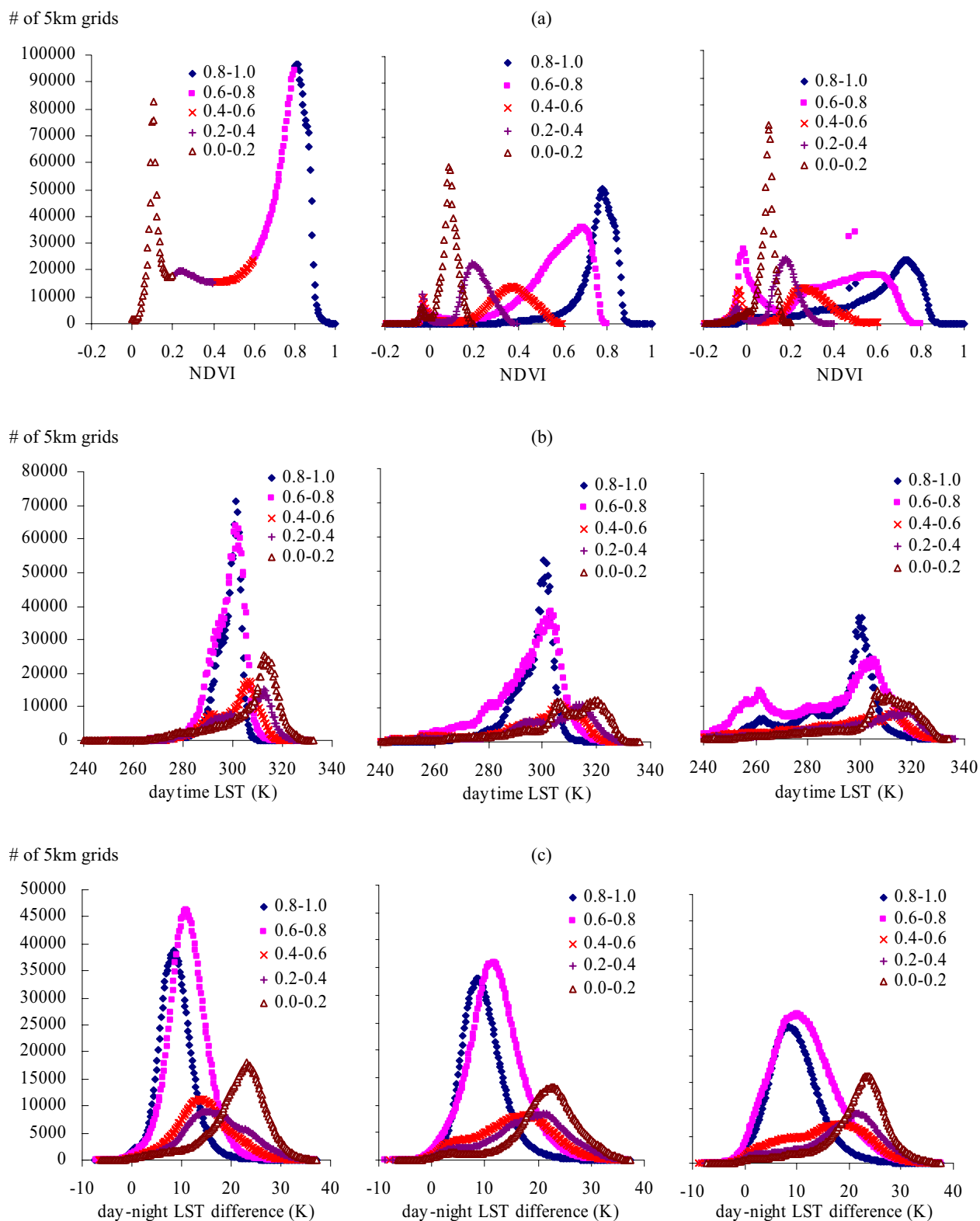


TABLE II. Mean and standard deviation (δ) values of NDVI, daytime LSTs and day-night LSTs in five NDVI peak zones.

Layer	NDVI		daytime LST		day-night LST difference		number of grids with LSTs
	mean	(δ)	mean (°C)	(δ) (°C)	mean (°C)	(δ) (°C)	
in the NDVI peak zone of 0.8 to 1.0							
1	0.8429	0.0284	24.96	5.38	8.724	3.552	1476258
2	0.8136	0.0451	24.79	5.53	8.879	3.599	1481741
3	0.7833	0.0680	24.14	6.52	9.153	3.872	1472496
4	0.7494	0.0951	23.24	7.92	9.370	4.096	1461050
5	0.7069	0.1263	22.11	9.80	9.591	4.402	1447721
6	0.6502	0.1654	20.16	12.16	9.499	4.578	1430770
7	0.5790	0.2053	17.83	14.94	9.334	4.791	1415002
in the NDVI peak zone of 0.6 to 0.8							
1	0.7239	0.0553	25.08	6.47	11.213	3.928	2026743
2	0.6833	0.0753	24.83	7.10	11.561	4.106	2037299
3	0.6256	0.1181	23.18	9.70	11.911	4.652	2023836
4	0.5580	0.1700	20.76	13.06	11.867	5.025	2020403
5	0.4891	0.2064	18.61	15.73	11.817	5.353	2023629
6	0.4196	0.2281	16.10	17.99	11.498	5.529	2024372
7	0.3489	0.2363	13.40	20.56	11.185	5.940	2028772
in the NDVI peak zone of 0.4 to 0.6							
1	0.5075	0.0586	27.42	9.10	14.247	5.552	708130
2	0.4570	0.0765	27.78	9.50	14.807	5.712	711114
3	0.3914	0.1116	26.11	13.05	15.084	6.236	712398
4	0.3249	0.1450	23.39	17.52	14.887	6.937	709320
5	0.2804	0.1535	22.24	18.73	15.106	7.149	707539
6	0.2495	0.1530	21.04	19.42	14.997	7.183	702404
7	0.2268	0.1524	20.01	20.27	14.883	7.436	702083
in the NDVI peak zone of 0.2 to 0.4							
1	0.2955	0.0572	30.22	10.62	16.826	6.294	698779
2	0.2624	0.0620	30.54	11.21	17.287	6.346	698010
3	0.2260	0.0764	29.25	14.45	17.519	6.749	696510
4	0.1958	0.0857	27.66	17.56	17.671	7.212	695923
5	0.1775	0.0874	27.56	18.26	18.076	7.259	694568
6	0.1644	0.0869	27.81	18.55	18.352	7.296	688912
7	0.1530	0.0878	27.37	19.42	18.279	7.378	677752
in the NDVI peak zone of 0.0 to 0.2							
1	0.1149	0.0372	33.64	12.36	20.913	6.008	983021
2	0.1033	0.0376	32.45	12.84	21.294	6.058	963079
3	0.0941	0.0393	32.92	14.75	21.391	6.255	936850
4	0.0868	0.0427	32.92	17.08	20.876	6.546	829195
5	0.0821	0.0464	32.90	18.10	20.900	6.736	758033
6	0.0823	0.0461	32.94	17.26	21.131	6.500	830555
7	0.0817	0.0445	32.18	16.70	21.009	6.342	854213

Fig. 3, Comparisons of NDVI (a), daytime LST and day-night LST difference in an irrigated grassland in Bridgeport (b) and a non-irrigated grassland in NV (c) in 2001.

