Semi-Annual Report Submitted to the
National Aeronautics and Space Administration

For July - December, 2002

Contract Number: NAS5-31370

Land Surface Temperature Measurements from EOS MODIS Data

MODIS Team Member
PRINCIPAL INVESTIGATOR

ZHENGMING WAN

P.I.'s Address:

Institute for Computational Earth System Science
University of California
Santa Barbara, CA 93106-3060

phone : (805) 893-4541
Fax no: (805) 893-2578
E-mail: wan@icess.ucsb.edu

Land Surface Temperature Measurements from EOS MODIS Data

Semi-Annual Report for July - December, 2002

Zhengming Wan

The calibration accuracies of Terra and Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) TIR bands in the atmospheric windows 3.5-4.3 μm and 8-13.5 μm were evaluated with in-situ measurement data of the lake surface temperature collected in Walker Lake, NV, in January 2003. The brightness temperatures at the top-of-atmosphere (TOA) calculated by the atmospheric radiative transfer code MODTRAN4.0 based on the in-situ measured lake surface temperatures and atmospheric profiles match well with the Aqua MODIS data within 0.2K in bands 22, 23, 29, and 31-32 in the early morning and afternoon passes in clear-sky conditions on 19 January. The calibration bias is 0.55K in band 20 and 0.8K in band 33. The combination of vicarious calibration results of Terra MODIS TIR bands from the Walker Lake field campaigns in October 2001 and January 2003 indicates that there is a variation of 0.2-0.35K in the calibration bias in bands 20, 22-23, 29 and 33. The averaged calibration bias of Terra MODIS agrees with the calibration bias of Aqua MODIS within 0.2K in bands 20, 22, 23, 29, and 31-33. Therefore, a combined use of Terra and Aqua MODIS data in these seven bands should improve the quality of MODIS LST products.

The accuracy of the MODIS LST product is validated better than 0.6K in three Terra cases and two Aqua cases with the in-situ measurement data collected in the Walker Lake field campaigns in 2001 to Jan. 2003

Refinements and improvements were made to the daily MODIS land-surface temperature (LST) product generation executive (PGE) code.

PGE codes for the daily, 8-day, and monthly LST products at climate model grids (CMG) were delivered to the MODIS team.

Recent Papers

Z. Wan, Y. Zhang, Q. Zhang, and Z.-L. Li, Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data, *Remote Sens. Environ.,* Vol. 83, pp. 163-180, 2002.

Z. Wan, Y. Zhang, Q. Zhang, and Z.-L. Li, The MODIS land-surface temperature products for regional environmental monitoring and global change studies, *Proceedings of IGARSS 2002, Toronto, Canada,* 2002.

Z. Wan, P. Wang, and X. Li, Using MODIS land-surface temperature and normalized difference vegetation index products for monitoring drought in the Southern Great Plains, USA, *Int. J. Remote Sens.,* accepted 2003.

Z. Wan, Y. Zhang, Q. Zhang, and Z.-L. Li, Quality assessment and validation of the MODIS global land-surface temperature, *Int. J. Remote Sens.,* accepted 2003.

Z.-L. Li, L. Jia, Z. Wan, and R. Zhang, A new approach for retrieving precipitable water from ATSR-2 split-window channel data over land area, *Int. J. Remote Sens.,* in press 2003.

L. Jia, Z.-L. Li, M. Menenti, W. Verhoef, and Z. Wan, A practical algorithm to infer soil and foliage component temperatures from bi-angular ATSR-2 data, *Int. J. Remote Sens.,* in press 2003.

1. Evaluation of The Calibration of MODIS TIR Bands

The land-surface temperature (LST) and sea-surface temperature (SST) retrievals require high quality of MODIS TIR data: low NEDT (noise equivalent temperature difference) and high calibration accuracy.

The channel-dependent noise and systematic error in Terra MODIS TIR channel data were evaluated with early MODIS data over lake and ocean sites in clear-sky days acquired with the old A-side of scan mirror and electronics before the end of October 2000. In 14 cases of sub-area sites with a size of 10 lines by 16 pixels each line, where the brightness temperature in band 31 changes within ± 0.1K, average and standard deviation values of brightness temperatures in ten channels (consisting a ten-element linear detector array) of 16 MODIS TIR bands show the channel-dependent noise and systematic errors. It is found that the NEDT specification is reached in all but three channels (the 9th in bands 21 and 24, and the 4th in band 22) of the 16 MODIS TIR bands. After a simple correction of the channel-dependent systematic errors with the statistics in the above 14 cases, the quality of the MODIS TIR data is significantly improved in bands 22-25, and 27-30 as shown in column 4 of Table I (Wan, 2002). We used the Terra and Aqua MODIS data over Lake Titicaca, Bolivia and Peru, on 16 June 2002 to estimate the NEDT values of the early Aqua MODIS TIR data. The granule ID is MOD021KM.A2002177.0300 for Terra MODIS and MYD021KM.A2002177.0600 for Aqua MODIS, respectively. The Terra and Aqua satellites passed over the same lake within three hours. The estimated NEDT values of Terra and Aqua MODIS TIR bands are shown in columns 5 and 6 of Table I. The channel-dependent systematic errors are not corrected in these two cases. It is worth mentioning that the effects of spatial and temporal variations in the atmospheric conditions are included in these estimated NEDT values. Comparison of the estimated NEDT values in these two columns indicates that Aqua MODIS has smaller NEDT values in most TIR bands.

In order to evaluate the calibration accuracy of the Aqua MODIS TIR data, we conducted two vicarious field campaigns in Walker Lake, Nevada, in 2002, once in August and another in November. The size of Walker Lake is approximately 20km long in the S-N direction and 7km wide in the E-W direction. The lake surface elevation is 1196m above sea level. There was no clear-sky day in these two campaigns which is good enough for the purpose of vicarious calibration. As shown in Table II, vicarious calibration of TIR bands requires clear-sky days without cirrus clouds, accurate measurements of atmospheric temperature and water vapor profiles and lake surface temperature. According to the spectral optical properties of the cirrus models in the MODTRAN code (Berk et al., 1999), the effect of standard cirrus (absorption and scattering) with optical depth 0.007 on the brightness temperature in MODIS TIR bands is shown in column 2, and the effect of thin subvisual cirrus with the same optical depth is shown in column 3. We used the atmospheric temperature and water vapor profile measured by Walker Lake in the early morning of 19 January 2003 just before the Aqua overpass as a baseline profile to study the effects of changes in atmospheric temperature, water vapor, ozone and CO_2 contents. The effects of increasing 0.5K in the atmospheric temperatures at levels up to 10km above sea level, increasing water vapor by 20%, reducing the ozone content by 6%, and increasing CO_2 by 10 ppm are shown in columns 4-7. The effect of an error of 0.2K in the lake surface temperature is shown in column 8. The accuracy for the calculated TOA brightness temperature to reach the specified calibration accuracy of the MODIS TIR bands is listed in the last column. These numbers indicate that in order to evaluate the calibration accuracy of the TIR bands in the atmospheric windows 3.5-4.3 μm and 8-13.5 μm at the specified levels, we need to measure the lake surface temperature at the 0.2K accuracy level, the atmospheric temperature and water vapor at the 0.5-1K and 20% accuracy levels in clear-sky conditions without thin cirrus for the Walker Lake site.

In the most recent field campaign conducted in January 2003, we measured the lake surface temperature with five TIR radiometers in clear-sky days. Four TIR radiometers were deployed in the middle of the lake to form a rectangle and the fifth one was deployed at the center. The diagonal distance of the rectangle is about 1.1km. Radiosonde balloons were launched by the lake shore 45 minutes before the overpass time of Terra and Aqua on the clear-sky days to measure the atmospheric temperature and water vapor profiles. The three profiles measured on 19 January shown in Figure 1 indicate that the atmospheric conditions were very stable at least in the 26 hours before the nighttime overpass of Terra MODIS until after the afternoon overpass of Aqua MODIS. Although there were clouds over Walker Lake on 17 January, the portion of Pacific Ocean near the California coastal line in Aqua MODIS granule 2003017.2115 was in clear-sky conditions. A sub-area of 10 lines by 16 pixels per line is found in which the standard deviation in the band 31 brightness temperature is 0.03K. The standard deviation values in all TIR bands are used as the new estimated NEDT values for Aqua MODIS shown in column 7 of Table I, with understanding that some effects of the spatial variation in atmospheric conditions are included in these estimated values. Even so the NEDT values of Aqua MODIS are still smaller than the NEDT values of Terra MODIS (column 4) in bands 22 and 31-33.

The TIR radiometers are the same type of radiometers used in our first successful vicarious calibration field campaign conducted in Lake Titicaca, Bolivia, during May 26 and June 17, 2000 (Wan et al., 2002). Routine calibrations with blackbody at temperatures from 0 to 50 °C indicates the calibration accuracy of the TIR radiometers is better than 0.2K. The same procedures were used to correct the effects of water surface emissivity and the atmospheric thermal infrared radiation reflected by the lake surface on the in-situ measurement data of TIR radiometers. To obtain the true value of lake surface kinetic temperature we need to add 0.53K to the values given by the TIR radiometers. The in-situ measurement data of the TIR radiometers before this correction are shown in Figure 2. Note that the time is in PST and the TIR radiometer data were recorded on only two or three dataloggers in Figure 2a because of the loose correction problem in the cables to other radiometers.

We calculated the band radiances and brightness temperatures (T_b) at the top-of-atmosphere with atmospheric radiative transfer code MODTRAN4.0 (Berk et al., 1999) based on the measured lake surface kinetic temperatures, and the atmospheric temperature and water vapor profiles measured by radiosondes launched on the lake-shore. The standard mid-latitude winter profile provided in the MODTRAN code was used to supplement the measured profiles at levels above 18km. The solar radiation is not included in the atmospheric radiative transfer simulations by assuming that the lake surface reflects the solar radiation like a specular mirror surface in the low wind speed conditions that prevailed in the clear-sky days during the field campaign. The comparisons between the calculated brightness temperatures and the brightness temperature values given by the MODIS data are shown in Table III. The TIR band number is given in column 1. The block of columns 2-4 is for the Terra MODIS daytime granule A2003018.1845 and the block of columns 5-7 is for the Terra MODIS nighttime granule A2003019.0545. The next two blocks with three columns each are for the Aqua MODIS nighttime and daytime granules A2003019.0955 and A2003019.2100. The top portion of the table gives detailed case descriptions for the four granules, including date, UTC time, the averaged latitude and longitude positions of the TIR radiometers, corresponding nearest scan line and sample numbers, granule ID, measured lake surface temperature and column water vapor, sensor zenith and azimuth angles, and the solar zenith and azimuth angles. Two rows are used for each band. The calculated T_b and MODIS T_b values, and their difference are given in the first row. The standard deviation in the MODIS T_b values at four pixels neighboring the averaged position of the TIR radiometers is given in the second row to show the spatial variation. The results for bands 34-36 are listed for reference only because these bands are more sensitive to the variation in the atmospheric temperature and CO_2 profiles as shown in Table II and the CO_2 profile was not measured in our field campaigns. But it may be useful to show the calibration bias with larger uncertainties: positive bias in bands 34-35 and negative bias in band 36 in most cases. These results are also consistent with the results from our vicarious field campaign in Lake Titicaca in June 2000. We will focus on the bands in the atmospheric windows 3.5-4.3μm and 8-13.5μm in the following analysis. The maximum value of the spatial variations in MODIS T_b values for all bands except band 21 is 0.13K in band 33. This indicates the high uniformity of the lake surface temperature.

As shown in columns 10 and 13 of Table III, the difference between calculated and MODIS T_b values in the eight TIR bands of Aqua MODIS is consistent in the nighttime (in column 10) and daytime cases (column 13). This T_b difference in the daytime case is about twice the difference in the nighttime case in bands 20 and 22 due to a small amount of reflected solar radiation. It seems reasonable to multiple the difference by a factor of 0.5 to remove the effect of reflected solar radiation. For the two cases (one daytime and one nighttime) of Terra MODIS in the first two blocks, the T_b difference is quite consistent in bands 29, and 31-33. It is reasonable for the T_b difference in band 20 to be slightly larger in the daytime case. The T_b difference values in band 21 are all within the specification. However, we cannot explain the unusual T_b difference values in bands 22 and 23: they are too large in the nighttime case. We checked the averaged temperature of the focal plane for these two bands, it is 83.40K in the daytime granule and 83.37K in the nighttime granule. Actually, this kind of focal plane temperatures is the normal operating temperature for the Terra MODIS instrument in the most time of two years since November 2000. In order to compare the calibration accuracies of bands 20, 22, and 23 for the Terra MODIS in its new A-side configuration, we used two more sets of results from vicarious calibration field campaigns conducted in Walker Lake, one daytime case in October 18, 2001 and another nighttime case in January 26, 2003. The results of four Terra MODIS cases are shown in Table IV. Considering the NEDT value in each band shown in Table I and possible small effects of solar radiation in daytime cases, we find that the T_b difference value looks consistent in all bands but bands 22 and 23. Finally, we have to attribute the unusual large values of the T_b difference in bands 22 and 23 of the nighttime granule A2003019.0545 to the effect of electronic crosstalk that cannot be explained by means of optical physics.

With the T_b difference values in Tables III and IV, we calculated the averaged calibration bias values and defined their ranges with the minimum and maximum values, the averaged value $\pm \delta T_b$ (the spatial variation in MODIS T_b), or the averaged value ± NEDT, whatever giving a wider range. These averaged calibration bias values and their ranges are shown in Figure 3 for the Terra and Aqua MODIS TIR bands 20, 22-23, 29, and 31-33. From this figure we can gain the following insights: 1) The calculated TOA T_b matches the Aqua MODIS data within 0.2K in bands 22, 23, 29, and 31-32 in the early morning and afternoon passes in clear-sky conditions on 19 January, the calibration bias is 0.55K in band 20 and 0.8K in band 33; 2) There is a variation of 0.2-0.35K in the calibration bias in bands 20, 22-23, 29 and 33 for the Terra MODIS data; 3) The averaged calibration bias of Terra MODIS agrees with the calibration bias of Aqua MODIS within 0.2K in bands 20, 22, 23, 29, and 31-33. Therefore, a combined use of Terra and Aqua MODIS data in these seven bands should improve the quality of MODIS LST products.

2. VALIDATION OF THE MODIS LST PRODUCT

We also used the in-situ measurement data collected in the Walker Lake field campaigns in 2001 to January 2003 to validate the MODIS LST product in three Terra cases and two Aqua cases as shown in Table V. The accuracy of the MODIS LST product is better than 0.6K in these five cases. The values in the last column of Table V indicates that the MODIS LST product has a positive bias ranging from 0.1K to 0.56K in the five cases. This small positive bias is consistent with our vicarious calibration results: there is a small negative bias in the calibration of band 32 relative to band 31 as shown in Figure 3. Small positive bias is also found in most cases of the early LST validation results (Wan et al., 2002).

3. REFINEMENTS AND IMPROVEMENTS TO PGE16

The following refinements and improvements were made to the collection 4 (version 4) daily MODIS land-surface temperature (LST) product generation executive (PGE) code PGE16: 1) update of the look-up tables (LUT) used in the day/night LST algorithm; 2) processing lake pixels in clear-sky at a confidence of 66% and higher; 3) using BRDF/Albedo parameters of the MODIS 16-day BRDF product (MOD43B1C) as input; 4) separating the range of viewing zenith angles into five sub-ranges (0-24°, 24-38°, 38-49°, 49-

58°, and 58-65°) instead of four in the version 3 code; 5) parallel processing of data in odd and even days to double the production rate and the storage of interim results for the day/night algorithm; 6) incorporating a split-window method into the day/night algorithm to ensure that the retrieved emissivities can be used by split-window algorithms.

4. CODE DELIVERY FOR THE CMG MODIS LST PRODUCTS

PGE codes for the daily, 8-day, and monthly LST products at climate model grids (CMG) were delivered to the MODIS team. A common grid size of 0.05° latitude and longitude for the MODLAND CMG products is used for the LST CMG products.

5. CONCLUSION

The averaged calibration bias of Terra MODIS agrees with the calibration bias of Aqua MODIS within 0.2K in bands 20, 22, 23, 29, and 31-33. Therefore, a combined use of Terra and Aqua MODIS data in these seven bands should improve the quality of MODIS LST products. The accuracy of the MODIS LST product is validated better than 0.6K in three Terra cases and two Aqua cases with the in-situ measurement data collected in the Walker Lake field campaigns in 2001 to January 2003.

Acknowledgment

This work was supported by EOS Program contract NAS5-31370 of the National Aeronautics and Space Administration.

REFERENCES

Berk, A., G. P. Anderson, L. S. Bernstein, P. K. Acharya, H. Dothe, M. W. Matthew, S. M. Adler-Golden, J. H. Chetwynd, Jr., S. C. Richtmeier, B. Pukall, C. L. Allred, L. S. Jeong, and M. L. Hoke, ‘‘MODTRAN4 radiative transfer modeling for atmospheric correction,’’ *Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research III, Proc. SPIE*, vol. 3756, pp. 348-353, 1999.

Wan, Z., ‘‘Estimate of noise and systematic error in early thermal infrared data of the Moderate Resolution Imaging Spectroradiometer (MODIS),’’ *Remote Sens. Environ.*, vol. 80, no. 1, pp. 47-54, 2002.

Wan, Z., 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, no. 3 , pp. 497-515, 2002.

Wan, Z., Y. Zhang, Q. Zhang, and Z.-L. Li, ‘‘Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data,’’ *Remote Sens. Environ.*, vol. 83, pp. 163-180, 2002.

TABLE I. The NEDT specification and estimated values of Terra and Aqua MODIS TIR bands.

(1) band	(2) bandwidth (μm)	(3) NEDT specified (K)	(4) Terra MODIS NEDT (K) estimated in 14 cases (Wan, 2002)	(5) Terra MODIS NEDT (K) estimated (2002177.0300) Lake Titicaca	(6) Aqua MODIS NEDT (K) estimated (2002177.0600) Lake Titicaca	(7) Aqua MODIS NEDT (K) estimated (2003017.2115) Pacific Ocean
20	3.660-3.840	0.05	0.06	0.09	0.07	0.06
21	3.929-3.989	2.00	0.64	0.85	1.89	1.26
22	3.929-3.989	0.07	0.07	0.16	0.06	0.06
23	4.020-4.080	0.07	0.05	0.17	0.11	0.14
24	4.433-4.498	0.25	0.13	0.28	0.18	0.29
25	4.482-4.549	0.25	0.08	0.22	0.18	0.20
27	6.535-6.895	0.25	0.12	0.43	0.21	0.28
28	7.175-7.475	0.25	0.09	0.60	0.14	0.10
29	8.400-8.700	0.05	0.03	0.13	0.09	0.08
30	9.580-9.880	0.25	0.08	0.35	0.21	0.36
31	10.780-11.280	0.05	0.03	0.05	0.05	0.03
32	11.770-12.270	0.05	0.05	0.07	0.07	0.04
33	13.185-13.485	0.25	0.16	0.36	0.11	0.11
34	13.485-13.785	0.25	0.27	0.31	0.14	0.15
35	13.785-14.085	0.25	0.23	0.27	0.16	0.17
36	14.085-14.385	0.35	0.41	0.53	0.22	0.21

TABLE II. Sensitivities of the calculated MODIS TIR band brightness temperatures on the variations in the atmospheric and surface conditions, and the δT_b(K) values required for the specified radiometric accuracies.

(1) band no.	(2) visible cirrus 64 μm mode	(3) subvisual cirrus 4 μm mode	(4) δT_a +0.5K (K)	(5) δwv +20% (K)	(6) δO_3 -6% (K)	(7) δCO_2 +10ppm (K)	(8) δT_s 0.2K (K)	(9) δT_b for specified accuracy (K) (%)
20	-0.15	-0.18	0.04	-0.04			0.17	0.16 (0.75%)
21	-0.16	-0.20	0.04				0.18	2.23 (10%)
22	-0.16	-0.19	0.04				0.19	0.22 (1%)
23	-0.16	-0.20	0.08			-0.01	0.17	0.22 (1%)
24	-0.18	-0.23	0.05			-0.10	0.03	0.20 (1%)
25	-0.18	-0.24	0.27	-0.01	0.01	-0.01	0.08	0.22 (1%)
27	-0.27	-0.34	0.45	-1.25				0.30 (1%)
28	-0.30	-0.36	0.42	-1.00	0.02			0.36 (1%)
29	-0.25	-0.36	0.08	-0.09	0.01		0.17	0.47 (1%)
30	-0.40	-0.28	0.05	-0.01	0.55		0.11	0.47 (1%)
31	-0.44	-0.30	0.04	-0.05			0.18	0.31 (0.5%)
32	-0.49	-0.46	0.06	-0.06			0.18	0.33 (0.5%)
33	-0.54	-0.60	0.23	-0.05	0.04	-0.19	0.09	0.65 (1%)
34	-0.56	-0.62	0.27	-0.06	0.03	-0.28	0.04	0.61 (1%)
35	-0.56	-0.64	0.24	-0.05	0.04	-0.26		0.58 (1%)
36	-0.68	-0.66	0.19	-0.02		-0.27		0.53 (1%)

TABLE III. Comparisons between MODIS TIR band brightness temperatures (T_b) and the calculated TOA T_b values in four clear-sky cases over Walker Lake, NV, on January 18 and 19, 2003.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
case des.	Jan. 18 18:45:29 UTC 38.6971°N, 118.7159°W (l, s) = (282, 543) Terra A2003018.1845 T_s = 279.08 K cwv = 0.91cm θ_v = 12.2° ϕ_v = 101.7° θ_s = 62.1° ϕ_s = 158.9°			Jan. 19 5:49:59 UTC 38.6971°N, 118.7159°W (2017, 871) Terra A2003019.0545 278.93 K 1.0cm 17.5° 79.3°			Jan. 19 9:59:24 UTC 38.6954°N, 118.7137°W (1828, 804) Aqua A2003019.0955 278.73 K 0.95cm 11.4° -77.9°			Jan. 19 21:03:36 UTC 38.6954°N, 118.7137°W (1522, 614) Aqua A2003019.2100 280.23 K 0.91cm 5.8° 100.4° 60.5° -164.3°		
band	calculated T_b (K)	MODIS	(3)-(2) (K)	calculated T_b (K)	MODIS	(6)-(5) (K)	calculated T_b (K)	MODIS	(9)-(8) (K)	calculated T_b (K)	MODIS	(12)-(11) (K)
20	277.99	278.80 (0.04)	+0.81	277.82	278.35 (0.11)	+0.53	277.26	277.80 (0.12)	+0.54	278.75	279.85 (0.11)	+1.10
21	277.52	276.38 (1.03)	-1.14	277.35	277.08 (2.05)	-0.27	276.76	278.60 (0.88)	+1.56	278.22	276.80 (3.82)	-1.44
22	277.57	277.80 (0.10)	+0.23	277.40	278.25 (0.22)	+0.85	277.17	277.33 (0.12)	+0.16	278.66	279.07 (0.04)	+0.41
23	276.41	276.47 (0.07)	+0.06	276.23	276.68 (0.05)	+0.45	276.12	276.07 (0.03)	-0.05	277.56	277.68 (0.04)	+0.12
29	276.66	276.67 (0.00)	+0.01	276.48	276.55 (0.07)	+0.07	276.34	276.38 (0.07)	+0.04	277.78	277.80 (0.03)	+0.02
31	278.21	278.29 (0.01)	+0.08	278.05	277.94 (0.07)	-0.11	277.78	277.72 (0.11)	-0.06	279.27	279.23 (0.01)	-0.04
32	278.00	277.90 (0.04)	-0.10	277.83	277.71 (0.04)	-0.12	277.48	277.34 (0.08)	-0.14	278.99	278.88 (0.03)	-0.11
33	262.81	263.36 (0.13)	+0.55	262.64	263.43 (0.13)	+0.79	262.33	263.12 (0.04)	+0.79	263.41	264.25 (0.06)	+0.84
34	252.66	253.46 (0.17)	+0.80	252.41	251.92 (0.27)	-0.49	252.15	253.19 (0.02)	+1.04	252.83	253.79 (0.16)	+0.96
35	243.73	245.72 (0.11)	+1.99	243.37	244.93 (0.23)	+1.56	243.01	244.27 (0.13)	+1.26	243.44	244.76 (0.23)	+1.32
36	229.94	228.35 (0.32)	-1.59	229.34	228.64 (0.24)	-0.70	228.51	226.78 (0.18)	-1.73	228.76	227.13 (0.17)	-1.63

TABLE IV. Comparisons between Terra MODIS TIR band brightness temperatures (T_b) and the calculated TOA T_b values in four clear-sky cases over Walker Lake, NV, on October 18, 2001 and January 18-19, 26, 2003.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
case des.	Oct. 18, 2001 18:56:31 UTC 38.6972°N, 118.7080°W (l, s) = (554, 685) A2001291.1855 T_s = 290.56 K cwv = 0.81cm θ_v = 0.7° ϕ_v = -100.2° θ_s = 49.6° ϕ_s = 165.9°			Jan. 18, 2003 18:45:29 UTC 38.6971°N, 118.7159°W (282, 543) A2003018.1845 279.08 K 0.91cm 12.2° 101.7° 62.1° 158.9°			Jan. 19, 2003 5:49:59 UTC 38.6971°N, 118.7159°W (2017, 871) A2003019.0545 278.93 K 1.0cm 17.5° 79.3°			Jan. 26, 2003 5:56:02 UTC 38.6971°N, 118.7160°W (471, 744) A2003026.0555 280.0 K 1.45cm 6.0° 77.4°		
band	calculated T_b (K)	MODIS	(3)-(2) (K)	calculated T_b (K)	MODIS	(6)-(5) (K)	calculated T_b (K)	MODIS	(9)-(8) (K)	calculated T_b (K)	MODIS	(12)-(11) (K)
20	289.04	289.67 (0.07)	+0.63	277.99	278.80 (0.04)	+0.81	277.82	278.35 (0.11)	+0.53	278.68	279.09 (0.06)	+0.41
21	288.50	289.20 (0.16)	+0.70	277.52	276.38 (1.03)	-1.14	277.35	277.08 (2.05)	-0.27	278.45	277.95 (1.37)	-0.50
22	288.59	288.74 (0.05)	+0.15	277.57	277.80 (0.10)	+0.23	277.40	278.25 (0.22)	+0.85	278.50	278.78 (0.06)	+0.28
23	286.99	286.91 (0.06)	-0.08	276.41	276.47 (0.07)	+0.06	276.23	276.68 (0.05)	+0.45	277.37	277.61 (0.07)	+0.24
29	287.09	286.97 (0.04)	-0.12	276.66	276.67 (0.00)	+0.01	276.48	276.55 (0.07)	+0.07	276.97	277.04 (0.05)	+0.07
31	289.15	289.24 (0.02)	+0.09	278.21	278.29 (0.01)	+0.08	278.05	277.94 (0.07)	-0.11	278.77	278.65 (0.09)	-0.12
32	288.75	288.80 (0.04)	+0.05	278.00	277.90 (0.04)	-0.10	277.83	277.71 (0.04)	-0.12	278.40	278.31 (0.07)	-0.09
33	269.65	270.63 (0.10)	+0.98	262.81	263.36 (0.13)	+0.55	262.64	263.43 (0.13)	+0.79	263.16	264.01 (0.13)	+0.85

TABLE V. Comparison between the MODIS LSTs and in-situ measured LSTs.

case no.	platform	granule ID	date & time (m/d/y hh:mm)	viewing zenith angle (°)	atmos. cwv (cm)	in-situ T_s from radiometers (K)	MODIS T_s (δT_s) (K)	MODIS - in-situ T_s (K)
1	Terra	A2001291.1855	10/18/01 18:56 UTC	0.7	0.81	290.56	290.74 (0.23)	+0.18
2	Terra	A2003018.1845	01/18/03 18:45 UTC	12.2	0.91	279.08	279.64 (0.09)	+0.56
3	Terra	A2003019.0545	01/19/03 05:50 UTC	17.5	1.0	278.93	278.99 (0.16)	+0.06
4	Aqua	A2003019.0955	01/19/03 09:59 UTC	11.4	0.95	278.73	279.05 (0.15)	+0.32
5	Aqua	A2003019.2100	01/19/03 21:04 UTC	5.8	0.91	280.23	280.53 (0.04)	+0.30

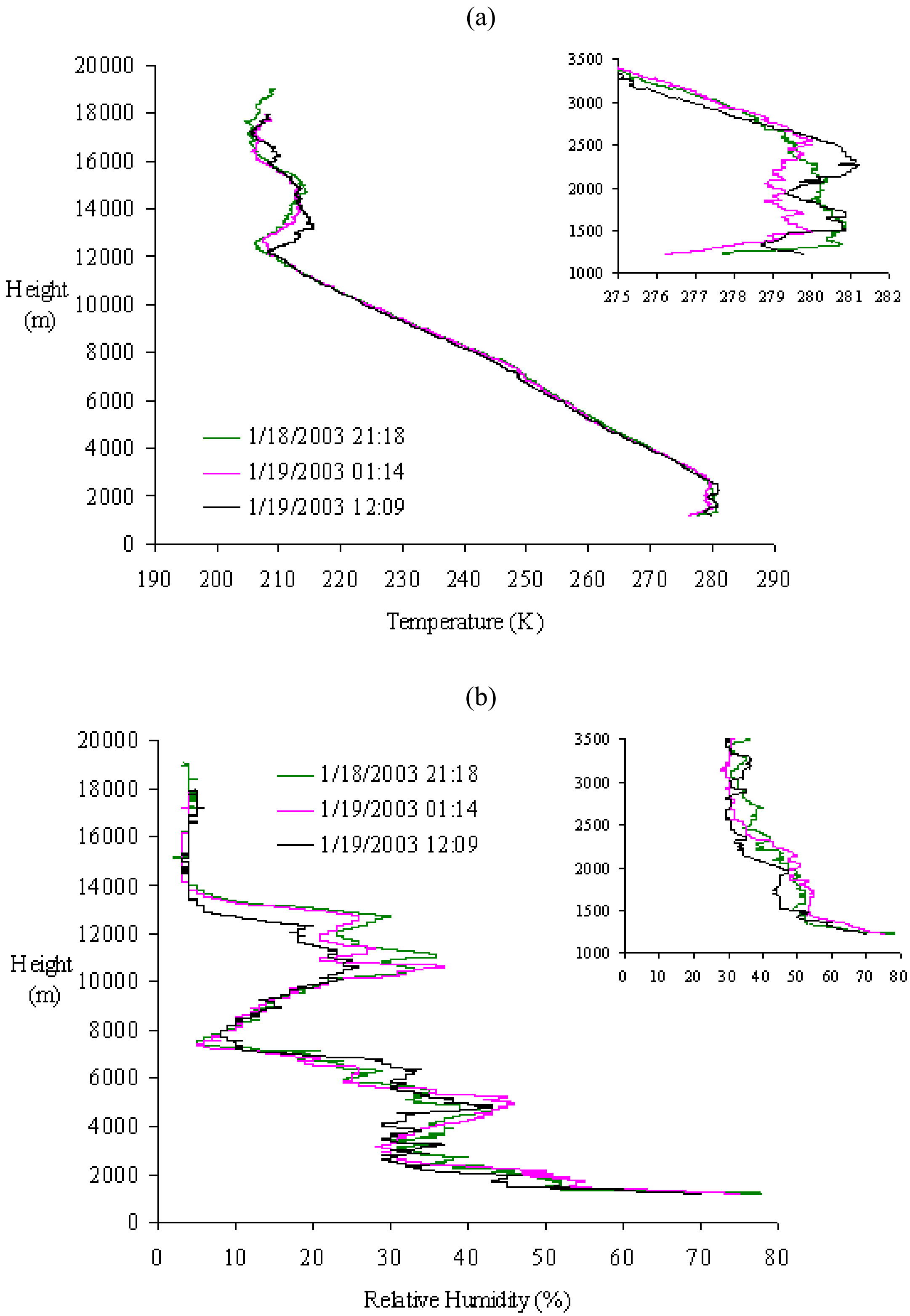
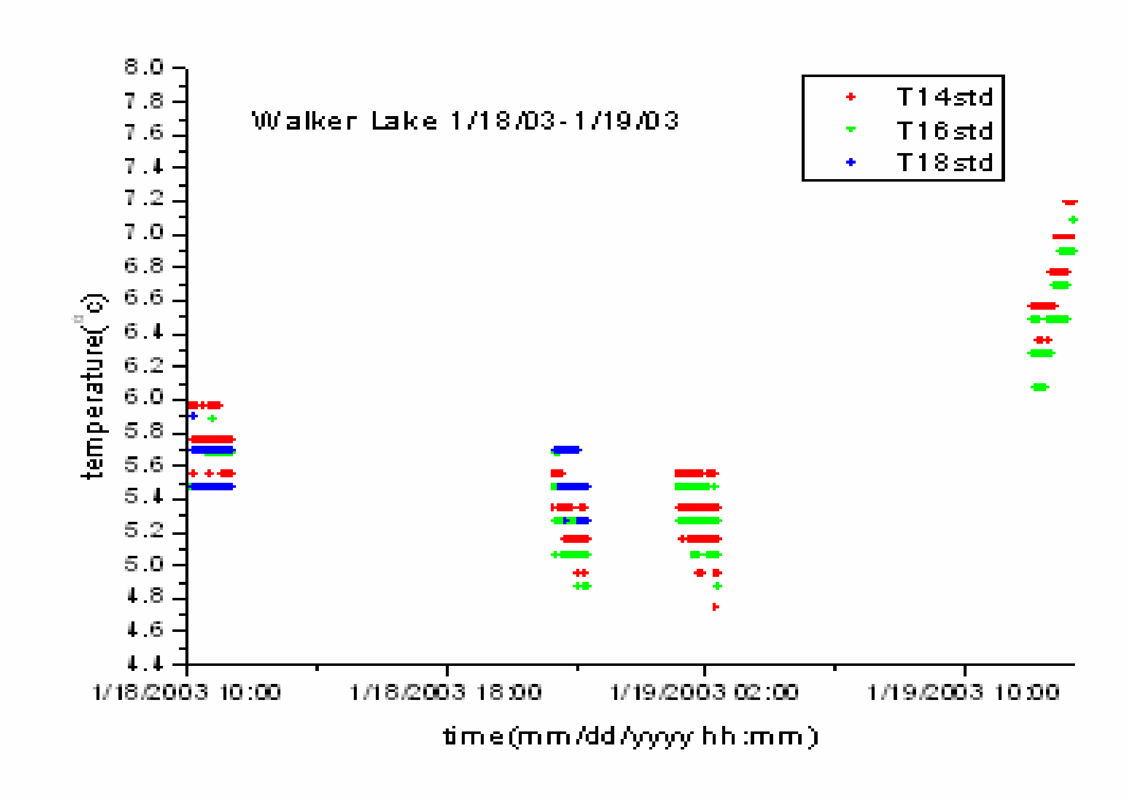


Figure 1. Atmospheric temperature (a) and water vapor (b) profiles measured by radiosondes at Walker Lake, NV, on January 18-19, 2003.

(a)



(b)

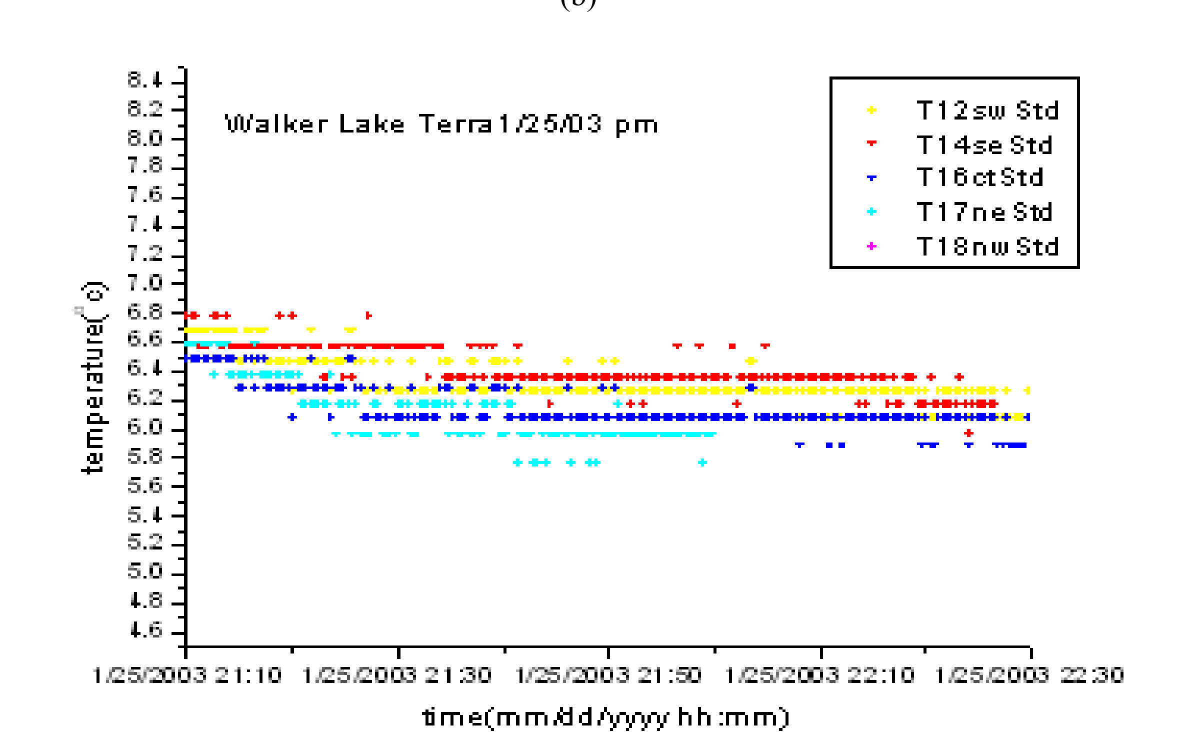


Figure 2. Lake surface temperatures measured with TIR radiometers in Walker Lake, NV, under clear-sky conditions in January 2003.

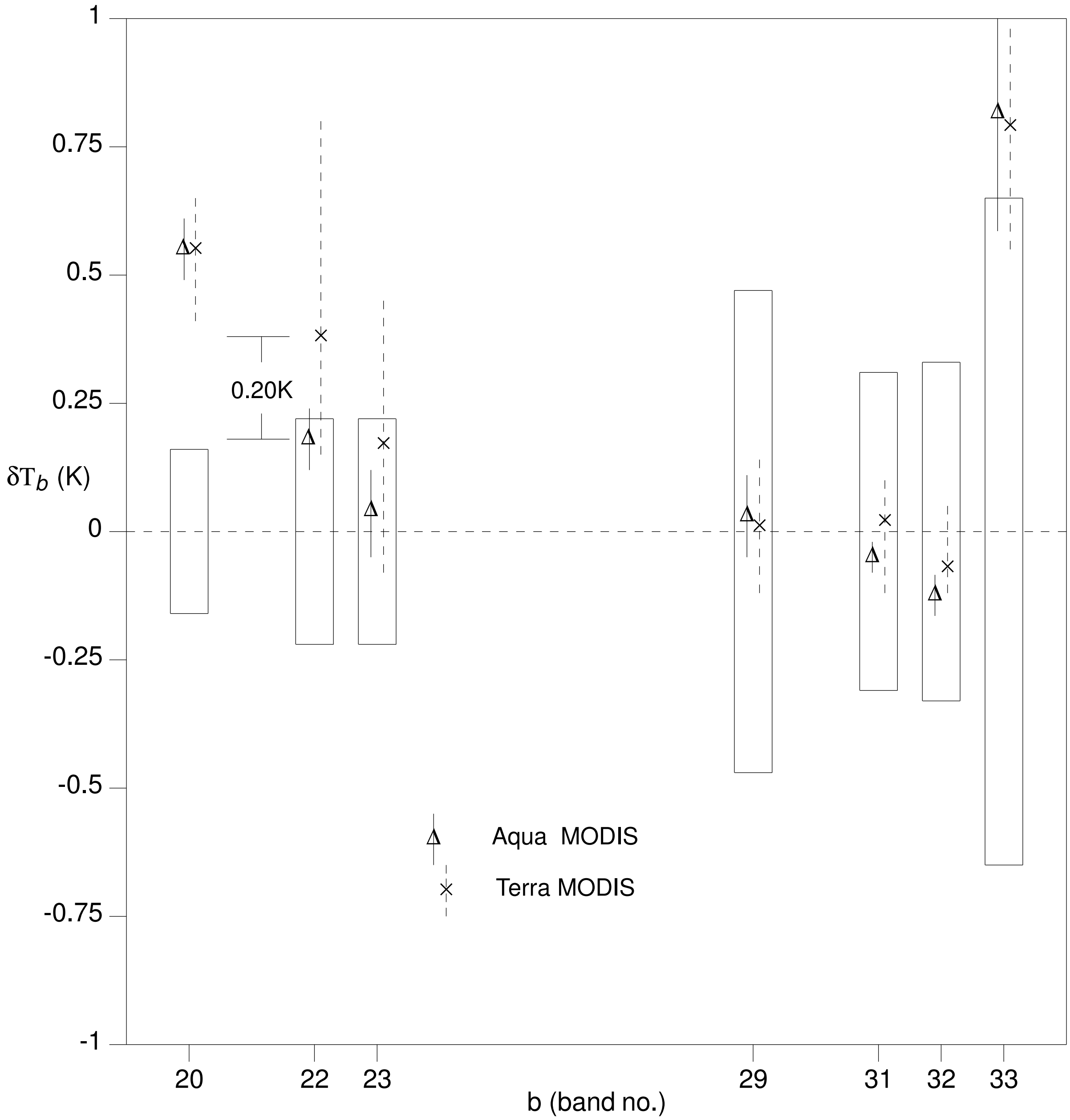


Figure 3. Calibration bias in the Terra and Aqua MODIS TIR bands 20, 22-23, 29, and 31-33, estimated from Walker Lake field campaigns conducted in 2001 and 2003.