Estimating Afternoon MODIS Land Surface Temperatures (LST) Based On Morning MODIS Overpass, Location, And Elevation Information

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Abstract

The MODerate Resolution Imaging Spectroradiometer (MODIS) instrument on-board the Terra and Aqua satellites is a critical tool for providing daily estimates of land surface temperature (LST). Terra launched in late 1999 has a morning (AM) overpass, whereas Aqua launched in early 2002 has an afternoon (PM). Generally, LST is expected, under cloudless conditions, to be warmer in the early afternoon than the morning due to the link between maximum skin temperature and solar insolation peak time, therefore the Aqua PM LST is likely to be closer to the maximum daily LST than that acquired from Terra. This letter investigated differences between the Aqua MODIS PM and Terra MODIS AM LST estimates over a range of land cover classes, locations, and dates, across Canada. The aim was to develop a simple adjustment which can be applied to Terra AM LST estimates to approximate a "synthetic" Aqua PM LST product from 2000 to mid 2002 thereby providing a seamless afternoon MODIS LST product from 2000 to 2006. Results indicate that there are statistically significant differences between the AM and PM LST ranging from 0.3° to 3.2°C depending on cover type, and between 1.2° and 5.0° depending on time of year. On average, over 90% of the variation observed in the PM record can be explained by the AM LST, land cover types and location.

1. Introduction

Remotely derived estimates of land surface (or skin) temperature are critical for climate and vegetation studies. The diurnal cycle of land surface temperature (LST) has been described by Trenberth (1984) and is composed of three parts: a climatic mean diurnal cycle, instantaneous variations and noise. The climatic mean diurnal system is dominated by the absorbed surface insolation which is principally driven by season, latitude and vegetation type (which in turn effects albedo and surface roughness). The instantaneous variations are due to the state of the atmosphere and surface properties, and are dominated by factors such as wind and soil moisture. The noise component represents small-scale fluctuations or random measurement error (Jin and Treadon 2003, Jin and Dickinson 1999).

Modelling of the mean diurnal system indicates that, while it may vary in amplitude in response to climate, its shape does not vary rapidly from day to day and depends primarily on sunset, sunrise, and the solar insolation peak time which, with some lag, effects the timing of the maximum daily skin temperature (Jin and Treadon 2003). It has been demonstrated therefore, through models and observations, that assuming the noise component can be ignored, the diurnal cycle of LST can be inferred from twice daily satellite measurements, in conjunction with a basic model of solar geometry (Jin and Treadon 2003).

The MODerate Resolution Imaging Spectroradiometer (MODIS) instrument on-board the Terra and Aqua provides near daily coverage of the Earth at 1-km resolution. Each satellite utilizes a near polar, sun-synchronous orbit with the Terra platform orbiting from north to south (descending node) with a morning (AM) equatorial crossing at 10:30am (local time). The Aqua platform travels from south to north (ascending node), crossing the equator in the afternoon (PM) at 1:30pm local time. Terra was launched in December 1999 with data available in late February 2000 and Aqua was launched in May 2002 with data available in July 2002. As a result no afternoon LST information is available from the MODIS sensor from the commencement of the MODIS archive in early 2000 until July 2002.

Due to the diurnal changes in LST described above, temperatures retrieved from Aqua and Terra will vary. For Canada solar insolation peak time ranges from 12 noon to 2.00 pm local time and as a result, Aqua LST's are likely to be closer to the maximum LST than those observed from Terra. Given that estimates of maximum daily LST provide a better indication of the thermal response of rising leaf temperatures caused by decreased latent heat flux as stomata close, and diurnal soil drought (Mildrexler et al. 2006) LST retrieved in the afternoon (by Aqua) are believed to be better suited for regional and global vegetation studies (Wan et al. 2004).

This letter investigates differences in the Aqua and Terra MODIS LST estimates across Canada. Given that the previous research has demonstrated that two LST observations can be used to derive the full diurnal LST cycle (Jin and Dickinson 1999), it is proposed that a simple transformation can be developed between the Terra AM LST's and Aqua PM LST, accounting for land cover, location and season, which will allow Terra AM observed LST's from 2000 – 2002 to be transformed to PM LST's with the ultimate aim to produce a seamless PM MODIS LST product from 2000 to 2006.

2. Methods

The MOD11A2 (Terra) and MYD11A2 (Aqua) LST products (collection 4) provide land surface temperatures for 8 day time periods by averaging the daily LST measurements using methods described in Wan et al. (2002). For this study four MODIS tiles (or granules) were selected which covered approximately 30 % of the Canadian land mass and included all major ecozones and vegetated land cover classes. AM and PM MODIS LST 8-day composites were downloaded for four time periods (Julian days 89, 185, 273, and 361) in 2003, resulting in a total of 16 granules per sensor. A total of 10,000 pixels were then randomly selected from each granule and the latitude and longitude calculated. The pixel elevation was determined from the USGS GTOPO30 coverage, which has a nominal spatial resolution of 30 arc seconds (≈ 1 km) (USGS 2006). The International Geosphere-Biosphere Program (IGBP) land cover scheme (MOD12Q1) (Friedl et al. 2002) for each pixel was also extracted with any pixel not assigned an IGBP vegetated class (i.e., snow, ice, urban, cloud; a total of 16% of the total randomly selected pixels) removed from further analysis. Three broad land cover classes: forest (IGBP classes 1 to 5; 25% of the total pixels selected), shrub/savanna/ grasses (IGBP classes 6 to 11, 40% of pixels selected), and crops (IGBP class 12, 16%) were developed and the dataset subset into a model development (comprising 80 % of the observations) and a validation set (the remaining 20 %).

Table 1: Location and elevation ranges of each of the four MODIS granules used in the analysis. ASL: above sea level.

Granule	South (°)	North (°)	West (°)	East (°)	Lowest (ASL (m))	Highest (ASL (m))
H10V03	50.16	60.17	-159.67	-109.00	0	3291
H11V04	40.00	50.00	-109.75	-78.41	131	978
H12V02	60.00	70.10	-165.80	-100.37	0	2332
H13V03	50.17	60.16	-99.88	-62.59	0	925

Initially, a t-test for independent samples was undertaken to establish if a statistically significant difference between the observed AM and PM LST existed across the broad vegetation cover types and the four seasons. Second, for each granule and cover type, multiple regression equations were developed between the observed PM LST as the dependent variable, with the AM LST, locational, and elevation data as independent variables for each cover type, time period and granule, resulting in 64 equations. Prior to model fitting, any non-linear trends in the data were examined. In all cases linear models were deemed the most suitable. After comparing the equations, the most suitable (based on the correlation and standard errors) was then applied to predict PM LST based on the AM LST, locational and elevation data, and results were assessed, using the independent dataset, to establish if any statistical differences remained.

3. Results

The morning and afternoon LST's, over the four seasons and cover types, were found to be significantly different using a t-test ($p < 0.001$) (Table 2). As expected, the PM LST values were warmer than the AM overpass by, on average, 1°C over all cover types. The smallest differences were for shrubs (0.3°C) and the largest for crops (2.1°C) and greatest in winter, and least in summer (0.3° to 1.4° respectively). In addition, the variances observed in LST within each granule indicates the PM LST values were more spatially variable than the AM LST, in most cases, by 1°C.

Table 2: ANOVA of LST from Aqua (PM) and Terra (AM), for forest, shrub, crop and all vegetated classes combined. Results of t-test are shown with high significance indicative of significant differences been the AM and PM datasets. N indicates number of cells in comparison.

	Mean (σ) (°C) LST PM (Aqua)	Mean (σ) (°C) LST AM (Terra)	*p* (*)	N
Forest	4.50 (14.6)	3.36 (14.1)	*0.0000*	32096
Shrub / Grasses	-2.30 (18.7)	-2.65 (17.8)	*0.0064*	51700
Crop	15.96 (11.3)	13.8 (11.7)	*0.0000*	20872
All Vegetation cells	**3.41 (17.7)**	**2.48 (16.9)**	***0.0000***	**104668**

(*) p indicates significance of two datasets being significantly different.

Correlation analysis confirmed that whilst the PM and AM LST values across all cover types were significantly different, they were also highly correlated. Across all land covers the Pearson product-moment correlation coefficient (r) ranged between 0.76 (for summer) to 0.98 (for spring). By cover type, the results were similar with forest and shrubs having similar correlations, and crops on average having a correlation 0.05 lower. Simple regression of the AM and PM LST provided an indication if what the offset was between the two datasets. Figure 1(a) indicates the offsets by cover type was 0.39°C, 1.45°C and 0.18°C for shrubs, forest, and crop classes respectively. The offset for all cover types combined was 0.89°C.

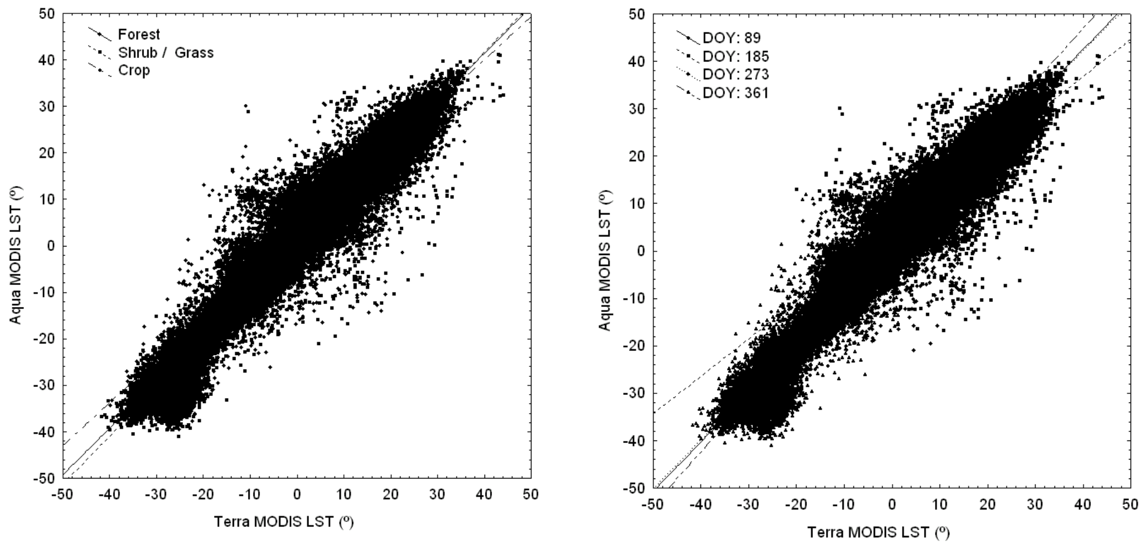

Figure 1 (a) and (b): Relationship between the Terra AM and Aqua PM LST values for the random selected pixels within 4 granules grouped by (a) broad land cover class and (b) time of year.

Examination of the regression equations relating the PM to AM LST's indicated that the coefficient of determinations (^{2}) were consistently lowest for crops and highest for all the cover classes combined, as demonstrated by Table 3 which shows the developed equations for all granules combined. Overall r^2 ranged between 0.13 - 0.96 with standard errors ranging from 1.2°C to 4.7°C (Table 3). The combined cover type, and the forest-only equations, for all locations and dates, were applied to the remaining 20 % of the observations as an independent validation. A second ANOVA and t-test was applied to confirm the predicted synthetic PM LST values, based on AM Terra data, were statistically similar to those observed by Aqua. Results confirm that over all cover types the PM LST predicted from AM Terra observations produced data statistically similar to Aqua observations with differences ranging less than 1°C (Table 4). Likewise, variations in temperature were comparable and differences were less than 0.6°C across all cover types.

Table 3: Subset of regression equations relating Aqua PM to Terra AM, latitude, longitude and elevation for individual and combined cover types for all locations combined. Models were assessed based on coefficient of determinations (r^2) and standard errors.

Cover Type	Significant Variables	r^2 (*)	SE (°C)	N
Forest	Terra LST, Latitude, Longitude, Elevation	0.95	3.25	32096
Grasses	Terra LST, Latitude, Longitude, Elevation	0.97	3.30	51700
Crops	Terra, Latitude	0.91	3.30	20872
All vegetated land covers	Terra LST, Latitude, Longitude, Elevation	0.96	3.2	104668

(*) significance of all models ($p < 0.0001$)

Table 4: ANOVA of LST from Aqua (PM) against the predicted PM LST's derived from the 20% independent dataset of Terra (AM), latitude, longitude and elevation for the forest, and all classes combined. Results of t-test indicate no significant differences been the AM and PM datasets. N indicates number of cells in comparison.

	LST PM (Aqua) Mean (σ) (°C)	LST Predicted using Table 2. Mean (σ) (°C)	*p* (*)	N
Forest	4.57 (14.5)	4.43 (14.3)	0.529	8128
All Vegetated Cells	**3.49 (17.6)**	**3.46 (17.4)**	**0.817**	**26568**

4. Discussion

Given that the MODIS archive can provide, in excess of 7 years of LST PM observations when the Aqua and Terra datasets are combined, calibrating the AM LST to a PM response is an informative endeavor. The results confirm that:

- There are statistically significant differences between the AM and PM LST's across all cover types and seasons across Canada.
- There is a highly significant relationship between AM and PM LST with the AM LST explaining more than 90 % of the variation observed in the PM LST record.

This relationship, is dependent however on cover type with crops being the poorest and forest being the highest.

- The differences between the AM and PM LST ranged from 0.3° to 3.2°C depending on cover type and between 1.2° and 5° depending on time of year.
- A simple (combined vegetation cover types and dates) regression equation, when applied to an independent subset of AM LST data, produced PM LST estimates that were statistically identical to those observed by the Aqua PM overpass.

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