ATMOSPHERIC CORRECTION OF LANDSAT THERMAL INFRARED DATA: A CALCULATOR BASED ON NORTH AMERICAN REGIONAL REANALYSIS (NARR) DATA

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ABSTRACT

In order to utilize Landsat thermal infrared data, we must account for atmospheric effects. Atmospheric correction applications currently available for this purpose either do not allow the user to specify atmospheric profiles for the desired time and location of the Landsat overpass and/or do not cover the entire Landsat operational period. To address these problems, we have developed an atmospheric correction application for the thermal infrared bands of Landsat-5 TM and Landsat-7 ETM+ that is applicable to North America and based on the MODerate spectral resolution atmospheric TRANsmittance algorithm and computer model (MODTRAN). Specifically, we have designed Interactive Data Language (IDL) programs to extract the desired atmospheric data from the North American Regional Reanalysis (NARR) data based on user inputs of latitude, longitude, elevation, and Landsat overpass time. The application reformats the atmospheric data and adds it to tape 5 inputs used in execution of MODTRAN. The application uses the MODTRAN tape 7 outputs to calculate atmospheric transmission, upwelling radiation and downwelling radiation parameters. We have compared our application with the online Atmospheric Correction Parameter Calculator (ATMCORR) that has been available to the public since 2003 (http://atmcorr.gsfc.nasa.gov). Comparisons using the two applications' normal atmospheric data types (NARR, NCEP) showed that parameter variances coincided with differences in the lowest portion of the atmospheric profile, indicating that the different methods used to handle this part of the profile may be the principle cause of variation between the applications.

KEYWORDS: atmospheric correction, Enhanced Thematic Mapper Plus (ETM+), Thematic Mapper (TM), thermal infrared (TIR), Landsat

INTRODUCTION

Two problems with current atmospheric correction applications for Landsat TIR data are that they either do not provide correction parameters for time periods prior to the year 2000 and/or do not allow the user to specify atmospheric profiles for a specific time and location. This may prevent users from utilizing important historical Landsat TIR imagery and/or lead users to rely on highly generalized standard atmospheric profiles for atmospheric correction, respectively. The objectives of this research were to develop an atmospheric correction calculator that covers the entire

Landsat operational period which allows the user to specify the time and site parameters for a specific Landsat overpass; then compare the new calculator to an existing online calculator.

METHODS

To address these objectives, we have developed the North American Atmospheric Correction Parameter Calculator (NAMCORR) for North American users. It has been designed specifically for Landsat-5 TM and Landsat-7 ETM+ thermal band (band 6) data and covers the entire Landsat operational period. The following sections describe the calculator and the process used to compare NAMCORR to the online calculator.

Calculator Description

NAMCORR is based on the online Atmospheric Correction Parameter Calculator (ATMCORR) which has been available to the public at http://atmcorr.gsfc.nasa.gov since 2003. Validation of ATMCORR by Barsi et al. (2005) revealed a bias of 0.5 ±0.8K for land surface temperatures (LSTs) generated using the correction parameters. More recently, Coll et al. (2010) found that LSTs derived from ETM+ at-sensor radiances showed differences from ground measured LSTs over rice fields in Valencia, Spain within the ±1.0K range. ATMCORR uses National Center for Environmental Prediction (NCEP) atmospheric data to provide global atmospheric data for 28 altitudes. In order to provide global coverage, NCEP uses a coarse 1^{o} by 1^{o} grid spatial resolution and six hour interval temporal resolution. Currently, ATMCORR only provides atmospheric correction parameters for dates after 19 January 2000 as this is when that dataset begins.

The NAMCORR application is an integrated set of Interactive Data Language (IDL) functions and procedures that (1) extract and convert data from gridded North American Regional Reanalysis (NARR) atmospheric data based on user inputs, (2) reformat and insert the data into a file used by the MODerate spectral resolution atmospheric TRANsmittance algorithm and computer model (MODTRAN), (3) send the file to MODTRAN for execution, and (4) extract the relevant data from the MODTRAN output and calculate the atmospheric correction parameters (Figure 1). ENVI / IDL software from ITT (ITT Visual Information Solutions at http://www.ittvis.com/ was used to write the application.

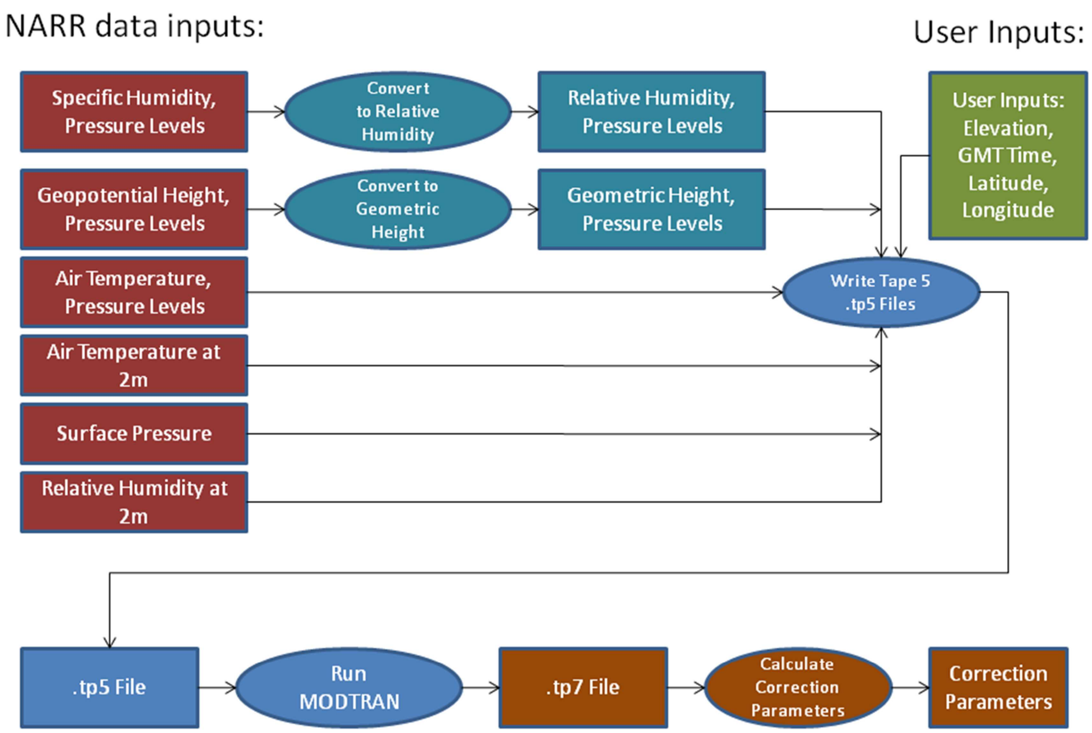

Figure 1. NAMCORR Processes.

NAMCORR uses NARR data, provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA. The data can be downloaded from http://www.esrl.noaa.gov/psd/ at no cost and are distributed in the network Common Data Format (.nc files). Users must download three monolevel data files and three pressure level data files which contain data for 29 atmospheric levels. The NARR data grid is approximately 32 by 32 km and provides data at three hour intervals.

NAMCORR extracts the necessary NARR data based on user inputs of Landsat overpass time, and the elevation, latitude, and longitude of the study area to create an atmospheric profile. NAMCORR uses the nearest location and closest time available in the NARR data without interpolation. This differs from ATMCORR which always interpolates between the two closest times, and which gives the user the option of using the nearest location or interpolating between the four nearest locations. The NARR monolevel data files include the temperature at 2m, relative humidity at 2m, and the surface pressure for the entire North American region for an entire year. NAMCORR extracts the surface layer parameters from the downloaded monolevel data files and incorporates them directly into the atmospheric profile. The three pressure level data files include the air temperature, geopotential height, and specific humidity at 29 pressure levels for the entire North American region for an entire month. The geopotential height data must be converted to geometric height, and the specific humidity must be converted to relative humidity before they are incorporated into the atmospheric profile.

To convert the geopotential altitude to geometric altitude the following equations provided by Mahoney (2001) are used with parameter values given in Table 1. The surface gravity is calculated based on the latitude of the study area and the equatorial gravity using:

$$\gamma_s(\varphi) = \frac{\gamma_e(1-k_s \sin(\varphi)^2)}{\sqrt{1-e^2\sin(\varphi)^2}} \tag{1}$$

A value for local radius of the earth is also calculated based in the latitude using:

$$R(\varphi) = \frac{6378.137}{1.006803 - 0.006706\sin(\varphi)^2} \tag{2}$$

The final calculation uses the previously derived local radius and surface gravity with the gravity at 45.542° N latitude and the geopotential altitude to calculate the geometric altitude using:

$$Z(H,\varphi) = \frac{R(\varphi)}{R(\varphi)\frac{\gamma_s}{\gamma_{45}} - H} \tag{3}$$

Table 1. Geopotential altitude to geometric altitude conversion parameters.

Parameter Name	Parameter Symbol	Parameter Value
eccentricity	e	0.081819 (km/km)
equatorial gravity	γ_e	9.7803253359 (m^{-2})
geometric altitude	Z	varies (km)
geopotential altitude	H	varies (km)
gravity at 45.542° N latitude	γ_{45}	9.80665 (m^{-2})
latitude	φ	varies (degrees)
local radius	$R(\varphi)$	varies (km)
Somigliana's Constant	k_s	.001931853
surface gravity	γ_s	varies (m^{-2})

Expressions provided by Andreas (2005) are used to convert specific humidity to relative humidity. The vapor pressure is calculated using the given specific humidity for the corresponding pressure level using:

$$e = \frac{qp}{0.622-0.37q} \tag{4}$$

where e is the vapor pressure (mb), p is the pressure (mb), and q is the specific humidity. The saturated vapor pressure is calculated based on the air temperature and pressure for the corresponding pressure level using:

$$e_s = 6.1121(1.0007 + 3.46 * 10^{-6} * p)\exp\left(\frac{17.502T}{240.97+T}\right) \tag{5}$$

where e_s is the saturated vapor pressure, and T is the air temperature (°C). The relative humidity (%) is calculated based on the previously derived vapor pressure and saturated vapor pressure using:

$$RH = \frac{e}{e_s}100 \tag{6}$$

To complete the atmospheric profile, NAMCORR splices one of two standard atmospheres onto the profile. Because NARR data only extend to approximately 17 km above sea level, either the mid-latitude summer or mid-latitude winter standard profile is added to the atmospheric profile beginning at 18 km above sea level. The complete atmospheric profile extends to 100 km above sea level, which is considered the top-of-atmosphere.

NAMCORR uses the atmospheric profile to create a tape 5 (.tp5) file which is sent to MODTRAN for execution. NAMCORR automatically generates and runs a second .tp5 file with the sensor location moved to one meter above the surface which is assigned an albedo of 1. This process is used to model the downwelling radiance.

MODTRAN generates two tape 7 (.7sc) files which NAMCORR uses to calculate the atmospheric correction parameters. The first output file includes transmittance and upwelling radiance values at 50 nanometer intervals. The second output file includes downwelling radiance values at 50 nanometer intervals. To calculate the transmittance atmospheric correction parameter, NAMCORR extracts the transmittance values from the .7sc file and integrates them using:

$$\tau = \sum \tau_i / n \tag{7}$$

where τ is the transmittance, τ_i is the transmittance as a function of wavelength from the .7sc file, and n is the number of wavelength intervals. The radiances are calculated using:

$$L = \frac{\sum L_i R_s \Delta\lambda}{\sum R_s \Delta\lambda} \tag{8}$$

where L_i is either the upwelling or downwelling radiance as a function of wavelength from the .7sc file, R_s is the corresponding sensor response from the Landsat-5 TM or the Landsat-7 ETM+ sensor response profile at each wavelength, and $\Delta\lambda$ is the wavelength increment. The limits of the integrations correspond to the values for the Full Width at Half Maximum of either the Landsat-5 TM or the Landsat-7 ETM+ sensor response profile.

Calculator Comparison

This section describes the data and methods used to compare NAMCORR to ATMCORR including site selection, the process for generating land surface temperature images using each calculator's atmospheric correction parameters, and the method for comparing the results. Note: neither NAMCORR nor ATMCORR parameters are validated in this study.

The sites and dates were selected to investigate the influence of climate, elevation, and season on the atmospheric correction calculations. The atmosphere is densest at the surface, so even minor differences in elevation can influence the prediction of the atmospheric parameters (Wang, White, and Robinson, 2000; Barsi et al., 2005). Two humid climate sites at different elevations were selected to maximize this effect. The third site was selected to compare the influence of humid and desert climates.

A series of six daytime Landsat scenes were selected for each site to investigate the affect of seasonal changes. Only cloud free or very low cloud cover scenes were used. All scenes were downloaded from the U.S. Geological Survey Earth Resources Observation and Science (EROS) Data Center which provides data processed to the L1G or L1T processing level. The sites and scenes selected were:

- Site 1: Approximately 35.7 km Southeast of Springfield, MO represents a mild humid climate with no dry season (C: Köppen Climate System) (Strahler and Strahler, 2006). Landsat-7 ETM+ scenes from October 2008 to November 2009 were used. The coordinates for the center of the site were 37°N 93°W and 0.4 km elevation.

- Site 2: Approximately 55.3 km Northwest of El Paso, TX represents a Desert/Steppe climate (BS/BW: Köppen Climate System) (Strahler and Strahler, 2006). Landsat-5 TM scenes from December 2008 to November 2009 were used. The coordinates for the center of the site were 32°N 107°W and 1.3 km elevation.
- Site 3: Approximately 176.8 km Southeast of Portland, OR represents a transition from a mild humid climate with no dry season to a highland climate (C/H: Köppen Climate System) (Strahler and Strahler, 2006). Landsat-5 TM scenes from March 2006 to October 2009 were used. The coordinates for the center of the site were 44°N 122°W and 1.4 km elevation.

The atmospheric correction parameters provided by NAMCORR and ATMCORR were used to derive a pair of LST images for all of the scenes. An IDL program was written to generate the scenes based on an approximation of the radiative transfer equation, which can be expressed as:

$$L_\lambda^{at-sensor} = \{\varepsilon_\lambda B_\lambda(T_s) + (1-\varepsilon_\lambda)L_\lambda^{atm\downarrow}\}\tau_\lambda + L_\lambda^{atm\uparrow} \quad (9)$$

where $L_\lambda^{at-sensor}$ is the at-sensor radiance (sometimes referred to as top-of-atmosphere radiance), τ_λ is the atmospheric transmissivity, $L_\lambda^{atm\downarrow}$ is the downwelling atmospheric radiance, $L_\lambda^{atm\uparrow}$ is the upwelling atmospheric radiance, ε_λ is the surface emissivity, and $B_\lambda(T_s)$ is the radiance emitted by a blackbody of kinetic temperature T_s (Barsi et al., 2005; Jiménez-Muñoz and Sobrino, 2006).

The temperature of an object can be obtained by reversing Planck's function. The Landsat specific approximation of the Planck function used to convert the calculated surface leaving radiance values to LST is expressed as:

$$T = \frac{k_2}{ln\left(\frac{k_1}{L_\lambda} + 1\right)} \quad (10)$$

where T is the temperature in Kelvin, k_1 and k_2 are Landsat calibration constants, and L_λ (represented as $\varepsilon_\lambda B_\lambda(T_s)$ in equation 9) is the surface leaving spectral radiance in $W/m^2 \cdot sr \cdot \mu m$, derived using the approximation of equation 9 (Barsi et al., 2005).

For each pair of LST images, the difference between the calculated correction parameters, and the difference between the generated LSTs were investigated. The atmospheric correction parameters were tabulated and the difference between NAMCORR and ATMCORR was calculated. ENVI software was used to stack the resulting LST image pairs for each scene. A 20 by 20 pixel sample centered on the site coordinates was extracted. A 20 by 20 pixel sample was chosen in order to restrict the samples to the area closest to the location for which the atmospheric correction parameters were calculated. The maximum, minimum, and range of the temperature were tabulated for each scene in a pair. Then the differences between each scene in a pair were calculated on a pixel by pixel basis to determine the minimum difference, the maximum difference, the range of the differences, the mean of the differences, and the standard deviation of the differences.

RESULTS

This section includes: a sample of selected atmospheric profiles, tables illustrating the differences between the atmospheric correction parameters and LSTs that were generated from using those parameters, illustrations of selected LST samples, and a follow-up investigation examining the influence of the first three kilometers of the atmospheric profiles on the calculation of the atmospheric correction parameters.

Profiles of the atmospheric data used by NAMCORR and ATMCORR as input to MODTRAN are shown in Figures 2, 3, and 4. Examples of pressure and temperature for Site 1 on 27 June, 2009 are illustrated in Figures 2 and 3. Visual inspection shows that the variability between the NARR and NCEP humidity profiles is greater than the difference between the NARR and NCEP pressure and temperature profiles for all the scenes. The main differences for the temperature profiles were in the 18-30 km altitude where NAMCORR and ATMCORR use different methods to splice the standard atmospheres to the model datasets.

A winter and summer graph of the relative humidity profile is presented for each site (Figure 4). The humidity levels are greater in the summer than in the winter for all the sites. The variation between the NARR and NCEP humidity profiles increases during the summer for sites 2 and 3. When the surface temperature, pressure, and humidity parameters and the elevation are entered in ATMCORR, the atmospheric profile is interpolated for the first three kilometers above the given elevation value. This is illustrated by the variation in profiles for the lower portion of the humidity profile graphs.

Atmospheric correction parameters were calculated using both NAMCORR and ATMCORR for each of the Landsat scenes (Table 2). Identical inputs for surface conditions (altitude, pressure, temperature and relative humidity) were used in NAMCORR and ATMCORR to generate the atmospheric profiles and corrections parameters. ATMCORR also provides the option to run the calculator without adding surface data: this option was not investigated in this research. An arbitrarily assigned emissivity value of 0.98 was used in all the LST calculations to simplify the image comparisons. The last three columns give the differences between the calculated parameters. The largest differences are between the downwelling values. They occur at sites 1 and 3, which have humid climates. The highest differences occur in the summer months, which is also when the humidity profiles for sites 2 and 3 show the greatest variation.

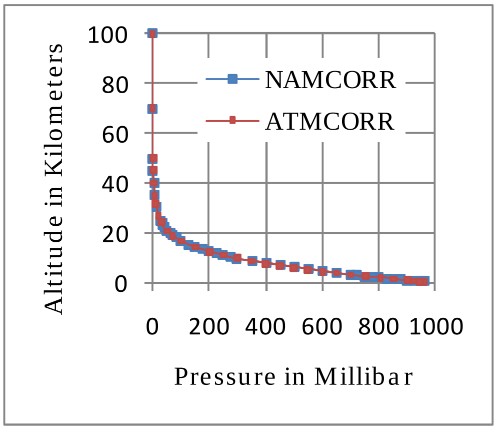

Figure 2. Site 1 Pressure Profile, 2009/06/27.

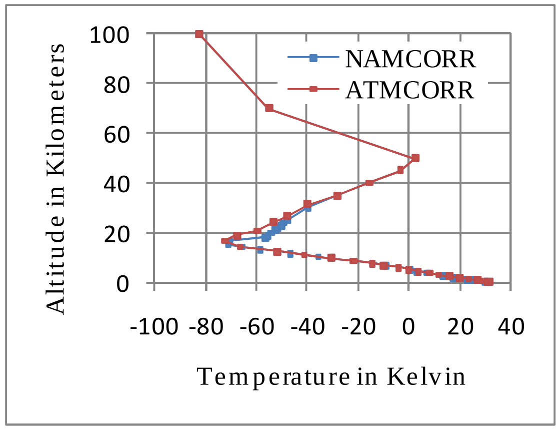

Figure 3. Site 1 Temperature Profile, 2009/06/27.

Figure 5 illustrates the 20 pixel by 20 pixel samples for selected dates at each site (these dates are the same as the atmospheric profiles in Figures 1, 2, and 3). The first column shows a false color infrared composite (RGB = 432) illustrating the general conditions on the ground. The second column shows the difference when the ATMCORR image values are subtracted from the NAMCORR image values on a pixel by pixel basis. All of the sites showed a greater range in values (2^{nd} column of images) for the summer than the winter. The greatest difference was at Site 1 in the summer. This may be because of the contrast between the densely vegetated portion and the portion with less vegetation (lower left corner). Site 1 shows more spatial variation in the difference values during the winter, while Sites 2 and 3 show more spatial variation in the summer scene (2^{nd} column). This may be because Site one has more variety in surface features in the winter due to less uniform vegetation cover. Increased summer variation for Sites 2 and 3may illustrate the increased affect of seasonal variation in insolation levels at higher elevations. The temperature and temperature difference data are given in Table 3.

The results indicate that elevation may exert a greater influence on the calculation of the atmospheric correction parameters than the variation in the humidity profiles or seasonal variation. Although the atmospheric profiles for Site 1 on 27 June 2009 appear to be the most similar of all the atmospheric profiles illustrated in Figure 4, this is also the site and date with one of the highest differences in the LST values (mean = 3.27 Kelvin). In contrast, Figure 4f) ATMCORR relative humidity values are approximately double the NAMCORR relative humidity values for the first 15 kilometers above sea level, yet the difference between the calculated LST values is much smaller (mean = -0.18 Kelvin). Note: scenes like Figure 4f) are not normally used for analysis, it was included due to the difficulty of obtaining a complete series of totally cloud free scenes for this site. The humidity profiles for Site 2 on 13 July, 2009 (Figure 4d) also show significantly higher relative humidity for ATMCORR profile from approximately 3-10km altitude, yet the mean difference between calculated LSTs is 0.18 Kelvin.

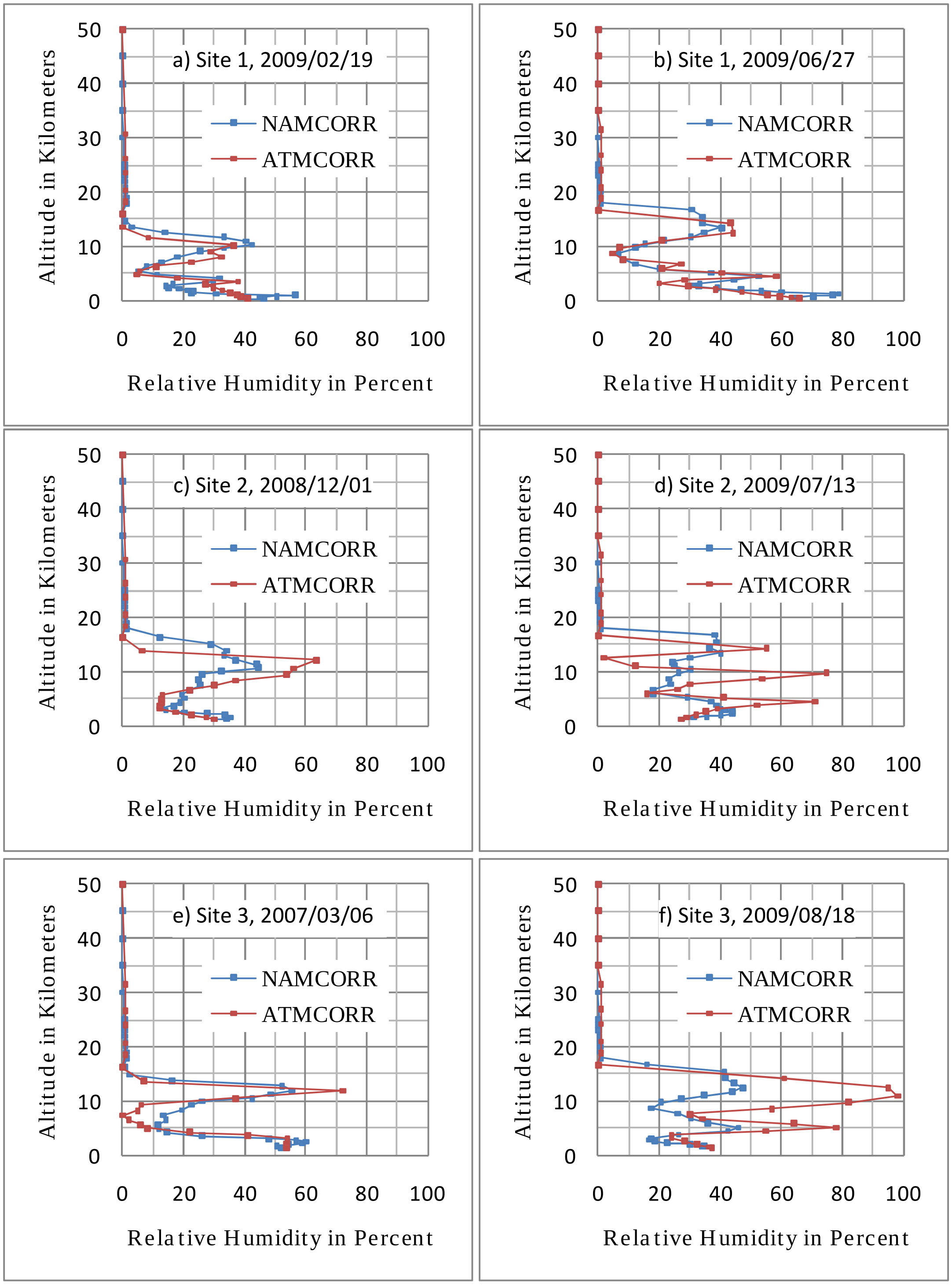

Figure 4. Humidity Profiles: in a) Site 1, 2009/02/19; b) Site 1, 2009/06/27; c) Site 2, 2008/12/01; d) Site 2, 2009/07/13; e) Site 3, 2007/03/06; f) Site 3, 2009/08/18.

Table 2. Atmospheric Correction Parameters for ATMCORR and NAMCORR.

Platform/ Location/ Elevation	Date	ATMCORR			NAMCORR			ATMCORR Minus NAMCORR		
		T[1]	U[2]	D[3]	T[1]	U[2]	D[3]	ΔT[1]	ΔU[2]	ΔD[3]
Site 1 Landsat-7 ETM+ 37°N 93°W 0.4 km	2008/10/30	0.86	1.05	1.73	0.823	0.924	2.105	0.037	0.126	-0.375
	2009/02/19	0.96	0.20	0.34	0.970	0.137	0.264	-0.010	0.063	0.076
	2009/04/08	0.92	0.57	0.97	0.930	0.439	0.783	-0.010	0.131	0.187
	2009/06/27	0.56	3.78	5.72	0.493	4.223	6.275	0.067	-0.443	-0.555
	2009/08/30	0.82	1.36	2.22	0.758	1.661	2.698	0.062	-0.301	-0.478
	2009/11/02	0.79	1.44	2.35	0.809	1.278	2.118	-0.019	0.162	0.232
Site 2 Landsat-5 TM 32°N 107°W 1.281 km	2008/12/01	0.94	0.38	0.65	0.917	0.401	0.917	0.023	-0.021	-0.267
	2009/03/23	0.94	0.37	0.65	0.940	0.376	0.672	0.000	-0.006	-0.022
	2009/05/10	0.90	0.77	1.34	0.929	0.536	0.950	-0.029	0.234	0.390
	2009/07/13	0.73	2.16	3.55	0.724	2.219	3.608	0.006	-0.059	-0.058
	2009/09/15	0.73	2.05	3.33	0.737	1.953	3.226	-0.007	0.097	0.104
	2009/11/02	0.94	0.43	0.74	0.925	0.391	0.910	0.015	0.039	-0.170
Site 3 Landsat-5 TM 44°N 122°W 1.418 km	2007/03/06	0.92	0.48	0.81	0.919	0.470	0.814	0.001	0.010	-0.004
	2007/05/09	0.89	0.72	1.24	0.888	0.705	1.217	0.002	0.015	0.023
	2009/05/30	0.80	1.36	2.28	0.853	0.973	1.669	-0.053	0.387	0.611
	2009/07/01	0.88	0.88	1.49	0.911	0.612	1.068	-0.031	0.268	0.422
	2009/08/18	0.82	1.28	2.17	0.856	0.999	1.704	-0.036	0.281	0.466
	2009/10/05	0.92	0.44	0.75	0.910	0.490	0.848	0.010	-0.050	-0.098

[1] Fractional transmittance (0-1.0); [2] Upwelling in $W/m^2/sr/\mu m$; [3] Downwelling in $W/m^2/sr/\mu m$

This indicates that there can be great differences in the humidity profile with small differences in calculated LSTs for sites at high elevations, while sites at low elevation with low variation in humidity profiles may generate relatively large LST differences. This illustrates that the lowest few kilometers of atmosphere are the most significant, especially the lowest portion of the relative humidity profile.

NAMCORR and ATMCORR have different approaches for the first three kilometers. NAMCORR uses the NARR data extracted from the surface and pressure level files without interpolation when generating the atmospheric profile used as input to MODTRAN. ATMCORR interpolates between the user input surface temperature, surface pressure, and surface relative humidity values and the NCEP data for the first 3 kilometers above the user input elevation value when generating the atmospheric profile used as input to MODTRAN.

To investigate the differences that may occur due to interpolating the lower portion of the atmospheric profile, the NARR data profiles used by NAMCORR were manually interpolated for three kilometers above the surface at site 1 and the comparison with ATMCORR was re-run. Comparison of the differences in parameter values for Table 2 and Table 4 show the the recalculated NAMCORR parameters were closer to the ATMCORR parameters for all atmospheric correction parameters and all dates.

The result of using interpolated and non-interpolated NARR data on the calculation of LST are compared in Table 5. For the three dates where the original differences were low, the interpolation results are similar to the original values. For the three dates where the original differences were high, the interpolation results in much larger changes. This implies that interpolating the lowest 3 kilometers of the atmospheric data used by the calculators (to calculate the atmospheric correction parameters) may have a significant influence on the calculation of the atmospheric correction parameters, and subsequently on any LST calculations based on those parameters.

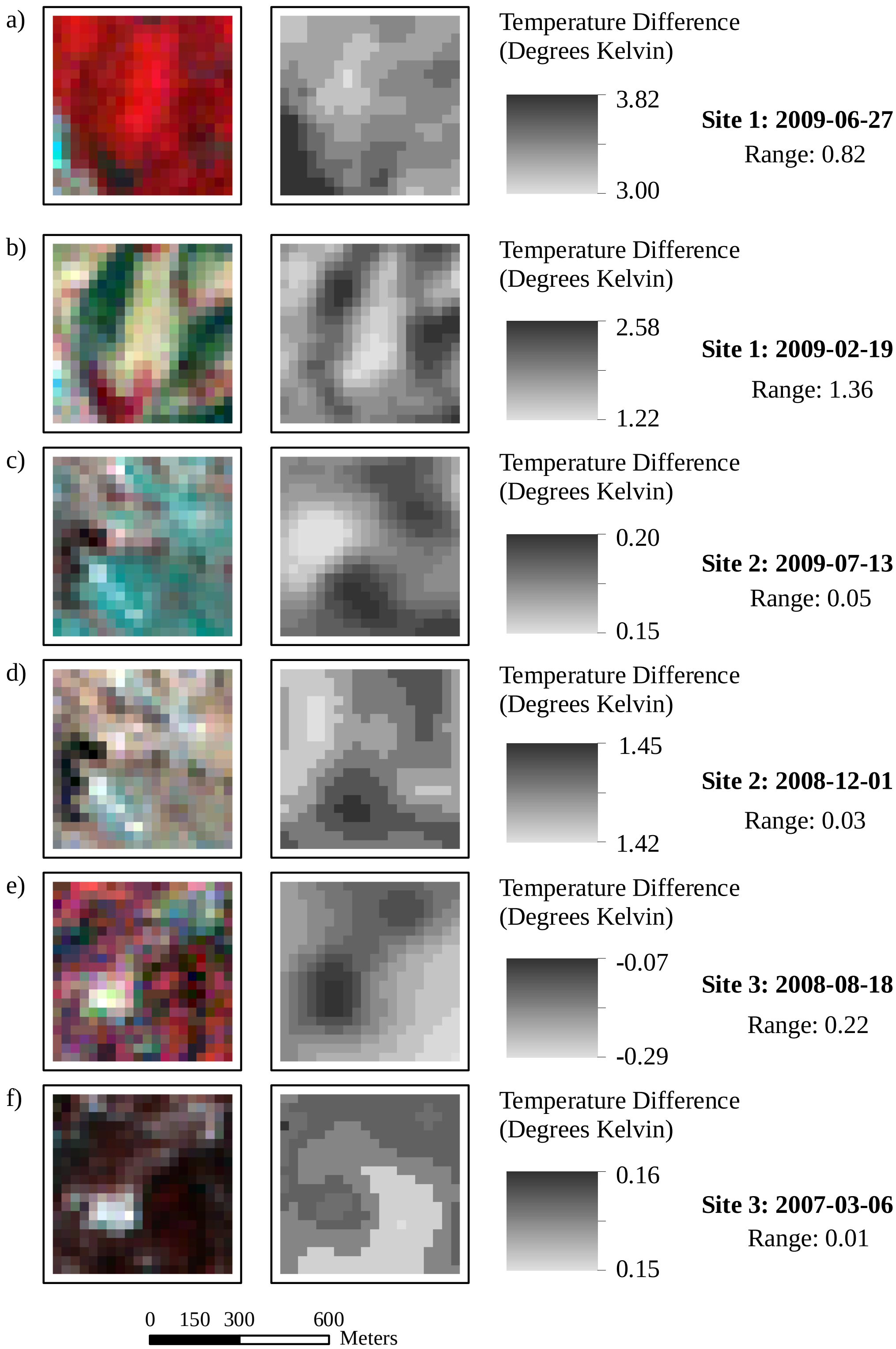

Figure 5. Left column: False color infrared composites (RGB = 4,3,2). Right column: NAMCORR minus ATMCORR difference images a) Site 1, 2009/06/27; b) Site 1, 2009/02/19; c) Site 2, 2009/07/13; d) Site 2, 2008/12/01; e) Site 3, 2009/08/18; f) Site 3, 2007/03/06.

Table 3. LST statistics and NAMCORR/ATMCORR difference statistics for 20 by 20 pixel samples.

Platform/ Location/ Elevation	Date	NAMCORR (Kelvin)			ATMCORR (Kelvin)			NAMCORR - ATMCORR Difference Statistics (Kelvin)				
		Min	Max	Range	Min	Max	Range	Min	Max	Range	Mean	σ
Site 1 Landsat-7 ETM+ 37^oN 93^oW 0.4 km	2008/10/30	291.9	296.3	4.4	291.5	295.8	4.3	0.422	0.473	0.051	0.440	0.010
	2009/02/19	275.6	282.0	6.4	273.0	280.9	7.9	1.220	2.576	1.356	1.908	0.283
	2009/04/08	294.2	302.5	8.3	293.8	302.2	8.4	0.279	0.395	0.116	0.340	0.025
	2009/06/27	306.4	314.9	8.5	303.4	311.1	7.7	3.000	3.820	0.821	3.272	0.142
	2009/08/30	295.7	301.1	5.4	293.5	298.6	5.1	2.212	2.523	0.311	2.287	0.068
	2009/11/02	293.2	299.7	6.5	293.2	299.8	6.6	-0.091	0.063	0.154	0.005	0.036
Site 2 Landsat-5 TM 32^oN 107^oW 1.281 km	2008/12/01	293.2	295.7	2.5	291.8	294.2	2.4	1.419	1.450	0.031	1.436	0.007
	2009/03/23	306.6	308.7	2.1	306.6	308.8	2.2	-0.566	-0.558	0.001	-0.056	0.000
	2009/05/10	328.6	324.4	4.2	325.2	329.6	4.4	-0.845	-0.955	0.110	-0.916	0.023
	2009/07/13	321.4	328.9	7.5	321.3	328.7	7.4	0.145	0.201	0.056	0.182	0.012
	2009/09/15	314.3	320.0	5.7	314.1	319.8	5.7	0.182	0.242	0.060	0.211	0.012
	2009/11/02	304.0	307.6	3.6	302.6	306.1	3.5	1.460	1.480	0.019	1.471	0.005
Site 3 Landsat-5 TM 44^oN 122^oW 1.418 km	2007/03/06	277.0	280.4	3.4	276.9	280.3	3.4	0.153	0.155	0.002	0.154	0.000
	2007/05/09	283.5	286.8	3.3	283.2	286.5	3.3	0.315	0.316	0.001	0.315	0.000
	2009/05/30	287.8	295.3	7.5	287.8	295.8	8.0	-0.028	-0.501	0.479	-0.218	0.095
	2009/07/01	296.7	302.4	5.7	296.6	302.5	5.9	0.092	-0.106	0.198	0.003	0.047
	2009/08/18	292.7	297.9	5.2	292.9	298.2	5.3	-0.069	-0.292	0.223	-0.184	0.050
	2009/10/05	275.1	276.3	1.2	275.0	276.2	1.2	0.123	0.134	0.012	0.130	0.003

Table 4. Atmospheric correction parameters for ATMCORR and NAMCORR interpolated NARR Data.

Platform/ Location/ Elevation	Date	ATMCORR			NAMCORR			ATMCORR Minus NAMCORR		
		T[1]	U[2]	D[3]	T[1]	U[2]	D[3]	ΔT[1]	ΔU[2]	ΔD[3]
Site 1 Landsat-7 ETM+ 37°N 93°W 0.4 km	2008/10/30	0.86	1.05	1.73	0.86	1.02	1.70	0.002	0.034	0.030
	2009/02/19	0.96	0.20	0.34	0.96	0.19	0.36	-0.001	0.006	-0.019
	2009/04/08	0.92	0.57	0.97	0.91	0.57	0.99	0.006	0.005	-0.018
	2009/06/27	0.56	3.78	5.72	0.51	4.13	6.19	0.048	-0.351	-0.470
	2009/08/30	0.82	1.36	2.22	0.81	1.44	2.35	0.015	-0.078	-0.134
	2009/11/02	0.79	1.44	2.35	0.79	1.40	2.31	-0.004	0.038	0.043

[1] Fractional transmittance (0-1.0); [2] Upwelling in W/m^2/sr/µm; [3] Downwelling in W/m^2/sr/µm

Table 5. Comparison of differences using interpolated and non-interpolated NARR data.

Platform/ Location/ Elevation	Date	NAMCORR - ATMCORR Difference Statistics (Kelvin)								
		Normal NARR Data				Interpolated NARR Data				ΔMean
		Min	Max	Range	Mean	Min	Max	Range	Mean	
Site 1 Landsat-7 ETM+ 37°N 93°W 0.4 km	2008/10/30	0.422	0.473	0.051	0.440	0.480	0.487	0.007	0.485	0.1
	2009/02/19	1.220	2.576	1.356	1.908	0.038	0.043	0.005	0.040	-1.7
	2009/04/08	0.279	0.395	0.116	0.340	0.503	0.526	0.023	0.514	0.2
	2009/06/27	3.000	3.820	0.821	3.272	1.571	2.168	0.598	1.770	-1.5
	2009/08/30	2.212	2.523	0.311	2.287	0.466	0.540	0.075	0.484	-1.8
	2009/11/02	-0.091	0.063	0.154	0.005	0.045	0.079	0.034	0.065	0.1

CONCLUSION

We have developed a new atmospheric correction parameter calculator based on an existing online calculator. The calculators were compared using LST images generated using the respective calculator's correction parameters. The results indicate that minor variations in atmospheric profile parameters at the lowest part of the profile may have a more significant affect than large variations in the atmospheric profile at higher altitudes. The difference between the handling of the lowest three kilometers of atmospheric data between NAMCORR and ATMCORR appears to result in significant differences between the calculated atmospheric correction parameters and should be the subject of future research. Future work should also include validating the atmospheric correction parameters generated by NAMCORR.

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REFERENCES

Andreas, Edgar L. 2005. Handbook of physical constants and functions for use in atmospheric boundary layer studies. U.S. Army Corp of Engineers, Engineering Research and Development Center. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA440352&Location=U2&doc=GetTRDoc.pdf

Barsi, Julia A., John R. Schott, Frank D. Palluconi, and Simon J. Hook. 2005. Validation of a web-based atmospheric correction tool for single thermal band instruments. *Proceedings of SPIE* 5882: 58820E-58820E-7.

Coll, César, Joan M. Galve, Juan M. Sanchez, and Vicente Caselles. 2010. Validation of Landsat-7/ETM+ thermal-band calibration and atmospheric correction with ground-based measurements. *IEEE Transactions on Geoscience and Remote Sensing, 48*(1): 547-555.

Jiménez-Muñoz, J. C., and J. A. Sobrino. 2006. Error sources on the land surface temperature retrieved from thermal infrared single channel remote sensing data. *International Journal of Remote Sensing, 27*(5): 999-1014

Mahoney, M.J. 2008. A discussion of various measures of altitude. Jet Propulsion Laboratory. http://mtp.jpl.nasa.gov/notes/altitude/altitude.html

Strahler, Alan, and Arthur Strahler. 2006. *Introducing Physical Geography.* Hoboken, NJ: John Wiley & Sons, Inc.

Wang, J., K. White, and G. J. Robinson. 2000. Estimating surface net solar radiation by use of Landsat-5 TM and digital elevation models. *International Journal of Remote Sensing, 21*(1): 31–43.