NOTES AND CORRESPONDENCE

Evaluation of the Relationship between Air and Land Surface Temperature under Clear- and Cloudy-Sky Conditions

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ABSTRACT

Clear and cloudy daytime comparisons of land surface temperature (LST) and air temperature (Tair) were made for 14 stations included in the U.S. Climate Reference Network (USCRN) of stations from observations made from 2003 through 2008. Generally, LST was greater than Tair for both the clear and cloudy conditions; however, the differences between LST and Tair were significantly less for the cloudy-sky conditions. In addition, the relationships between LST and Tair displayed less variability under the cloudy-sky conditions than under clear-sky conditions. Wind speed, time of the observation of Tair and LST, season, the occurrence of precipitation at the time of observation, and normalized difference vegetation index values were all considered in the evaluation of the relationship between Tair and LST. Mean differences between LST and Tair of less than 2°C were observed under cloudy conditions for the stations, as compared with a minimum difference of greater than 2°C (and as great as 7+°C) for the clear-sky conditions. Under cloudy conditions, Tair alone explained over 94%—and as great as 98%—of the variance observed in LST for the stations included in this analysis, as compared with a range of 81%–93% for clear-sky conditions. Because of the relatively homogeneous land surface characteristics encouraged in the immediate vicinity of USCRN stations, and potential regional differences in surface features that might influence the observed relationships, additional analyses of the relationships between LST and Tair for additional regions and land surface conditions are recommended.

1. Introduction

Land surface temperature (LST) is a key variable in determination of the land surface energy budget and is thus often assimilated into land surface models (Rodell et al. 2004). LST (as soil or vegetation canopy temperature) is also used in models of vegetation stress (e.g., Jackson et al. 1981; Moran et al. 1994; Anderson et al. 2007). When observed over multiple years, LST can also be assessed for climatic trends (e.g., Jin 2004). Because of the relatively small network of in situ observations and its relatively large spatial variability, LST is most commonly measured on a regional or global basis with satellite retrievals. Because of the regional–global availability of satellite-derived LST data, it is often used to estimate near-surface air temperature (e.g., Cresswell et al. 1999; Prihodko and Goward 1997; Stisen et al. 2007). However, as LST data retrieved from the Geostationary

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Operational Environmental Satellite (GOES) and other satellites are increasingly utilized (e.g., Anderson et al. 2007), the routine availability of LST becomes a concern. The next generation of GOES satellites will optimally observe LST at 5-min intervals over the conterminous United States with thermal infrared sensors under cloud-free conditions (Schmit et al. 2005), although operational LST products are anticipated to be at hourly intervals. However, when cloudy conditions exist and LST data are unavailable from satellites, other methods must be relied upon to infer surface properties of interest (e.g., Anderson et al. 2007). The accuracy of LST products derived from current satellite sensors is nominally 0.5 K or greater (e.g., Wan et al. 2004). The required accuracy for the LST from the future GOES-R Series (GOES-R) is 2.3 K (Yu et al. 2009), while the requirement for the Visible Infrared Imaging Radiometer (VIIRS) is 1 K (NPOESS 2001). As part of an evaluation of the potential use of in situ LST data to validate satellite-derived LST (Hale et al. 2011), the relationship between near-surface air temperature (Tair) and LST under clear- and cloudy-sky conditions is examined in this study. Although Tair is recognized as generally dependent on LST, if there is a robust relationship between LST and Tair during cloudy conditions, then routinely observed Tair might be used to estimate LST when direct observations from satellites are unavailable. The objective of this study was to examine and compare the relationship between Tair and LST observed for in situ stations during clear and cloudy conditions to determine if Tair might be used in estimation of LST.

2. Methodology

The clear and cloudy daytime comparisons of LST and Tair were made for 14 stations in the U.S. Climate Reference Network (USCRN) of climate-quality meteorological observation stations (NOAA/NESDIS 2002). This subset of USCRN stations includes seven ''pairs'' of stations located within 30 km of each other (Table 1). These paired stations have identical instruments. Five of the station pairs were utilized by Gallo (2005) in a comparison of air temperature and lapse rate differences between the pairs of stations. The inclusion of the paired stations in this study permits comparisons of the relationship between LST and Tair between locations within close proximity to each other. A general site description of the USCRN stations is provided at http://www.ncdc.noaa.gov/crn/sitedescription.html, with photographs of the individual stations provided at http://www.ncdc.noaa.gov/crn/photos.html. A map of the locations of the paired stations included in this analysis, as well as the other USCRN stations, is provided at http://www.ncdc.noaa.gov/crn/stationmap.html. The latitude, longitude, and elevation information for several of the stations (Table 1) has been updated from that cited in Gallo (2005).

TABLE 1. Elevations, latitude and longitude, and horizontal distance between stations for the USCRN station pairs utilized in this study.

Station	Elev (m)	Lat (°N)	Lon (°W)	Distance (km)
Asheville 8SSW	655.2	35.49	82.61	9.9
Asheville 13S	641.0	35.42	82.56	
Durham 2N	37.3	43.17	70.93	7.1
Durham 2SSW	19.2	43.11	70.95	
Kingston 1NW	35.0	41.49	71.54	1.4
Kingston 1W	32.3	41.48	71.54	
Lincoln 11SW	418.2	40.70	96.85	29.7
Lincoln 8ENE	362.4	40.85	96.56	
Newton 8W	53.64	31.31	4.47	13.6
Newton 11SW	47.55	31.19	84.45	
Stillwater 2W	271.3	36.12	97.09	2.4
Stillwater 5WNW	270.7	36.13	97.11	
Wolf Point 34NE	805.6	48.49	105.21	21.6
Wolf Point 29ENE	635.5	48.31	105.10	

The hourly LST and Tair data observed at the 14 stations between 1 January 2003 and 31 December 2008 were included in this analysis. The air temperature observations at the USCRN stations are made with three Thermometrics platinum resistance thermometers that are individually housed in aspirated solar shields. The observations from the three thermometers are used to derive a single ''official USCRN temperature'' value for each hour (http://www.ncdc.noaa.gov/crn/elements.html#temp) based on measurements made every 2 s, averaged over 5 min, and then averaged over 1 h. The functional requirement for measurement of air temperature is an accuracy of ±0.3°C for the range of −50° to +50°C (NOAA/NESDIS 2007).

The LST observations are made with an Apogee Instruments infrared temperature sensor (IRTS-P). Similar to the air temperature, LST is measured every 2 s and then averaged over 5-min intervals (http://www.ncdc.noaa.gov/crn/elements.html#ir). The values included in this study are the routinely reported 1-h averages of the 12 five-min observations (e.g., http://www.ncdc.noaa.gov/crn/observations.htm). In addition to the LST and hourly values of air temperature, incident (incoming downward) shortwave solar radiation and wind speed were acquired for each station. The functional requirement for measurement of LST is an accuracy of ±0.5°C (NOAA/NESDIS 2007).

A summary of the other current instruments included at the USCRN stations and their specifications is also provided in NOAA/NESDIS (2007).

TABLE 2. Criteria for potential observations and for clear- and cloudy-sky observations used in the analysis.*

1) Incident solar radiation for hourly obs >25 W m^{-2} at each station
2) Air temperature from −50° to 50°C at each station
3) LST from −30° to 70°C at each station
4) (i) Clear sky: measured solar radiation at each station >90% of estimated max hourly value and reported clear-sky cover
(ii) Cloudy sky: measured solar radiation at each station <50% of estimated max hourly value for interval ±2 h of obs time and reported overcast sky cover

* Potential observations met criteria 1–3 above; actual clear- or cloudy-sky observations met criteria 1–4.

Surface emissivity values are not included in the standard computation of LST reported for the USCRN stations. Land surface characteristics at the USCRN station locations are recommended to be consistent throughout the USCRN network. Vegetation at each station site is specified as ''grass/low vegetation ground cover'' (NOAA/NESDIS 2002) and normal maintenance includes mowing of the vegetation (NOAA/NESDIS 2003); however, mowing can be less consistent at the more remote station locations and result in grass heights of up to 12 inches (M. A. Palecki 2010, personal communication). Because of the recommended consistency of vegetation, land surface emissivity values were assumed constant for the USCRN station observations and no adjustments were made to the reported LST values.

The data for each of the pairs of stations were matched by observation day and hour. During data validation for a pair of stations, if any of the variables were determined to be invalid for a given hour, then all variables for each of the stations of that pair of stations were deleted for that hour. Daytime observations were defined by criteria 1 listed in Table 2 (incident solar radiation for hourly observation >25 W m^{-2}). Determination of whether observations were made during periods of ''clear sky'' or ''cloudy sky'' was accomplished through two methods. First, hourly theoretical maximum values of incident solar radiation were calculated. These values were based on top-of-atmosphere irradiance for a given location, time, and day of year, which then was adjusted for attenuation occurring over the radiation pathlength due to estimated water vapor (Smith 1966), dry atmospheric gases, and aerosols (Myers and Dale 1983). Water vapor was derived from hourly data observed at nearby in situ stations (NOAA/NCDC 2009), as dewpoint values were not measured at the USCRN stations. Comparisons were made between the measured hourly solar radiation value and its corresponding maximum theoretical value to make an initial classification of clear or cloudy. The measured hourly solar radiation value was required to be greater than 90% of the modeled value to be considered a clear-sky observation, while a measured value of less than 50% of the theoretical maximum resulted in an initial cloudy-sky determination. Additionally, to assure cloudy-sky conditions truly existed, the 50% or less of theoretical maximum hourly solar radiation criteria must have been observed for 2 h prior to and 2 h after an observation for the observation to be designated as cloudy sky.

The second method for determination of clear- or cloudy-sky conditions utilized sky cover observations included with the hourly dewpoint data used in estimation of water vapor (NOAA/NCDC 2009). For this study, a final clear-sky classification necessitated both an initial clear-sky classification (as described in above paragraph) and that a clear-sky condition was reported in the available hourly dataset (NOAA/NCDC 2009). Similarly, final classification as cloudy-sky conditions required a reported ''overcast sky'' condition. The criteria used in data validation and clear–cloudy categorization are summarized in Table 2. These criteria were selected to exclude hours with partial cloud cover or optically thin clouds and to make sure that hours included in the datasets were unambiguously clear or cloudy.

To accommodate comparisons between the pairs of stations, observations from both stations were required to have identical clear- or cloudy-sky conditions for further analysis. Linear regression models were used to evaluate the relationship between LST and Tair for the seven station pairs. Analyses were completed for both the clear- and cloudy-sky conditions.

3. Results and discussion

a. Characteristics of clear- and cloudy-sky observations

The frequency of clear-sky observations as utilized in this study (number of actual clear-sky observations compared to total number of daytime observations) varied with the stations, ranging from 3.7% for the Kingston, Rhode Island, stations to 38.8% for the Stillwater, Oklahoma, stations (Fig. 1). The frequency of cloudy-sky observations varied from 3.5% (Newton, Georgia, stations) to 11.6% (Kingston). Except for Kingston, the frequency of clear-sky observations for the examined stations was at least 10% greater than the frequency of cloudy observations over the study interval.

The Kingston stations showed significant differences from the other stations of this study in terms of their clear-sky climatologies. The relative paucity of clear-sky observations for the stations (917 observations) was a direct consequence of utilizing the observed sky cover

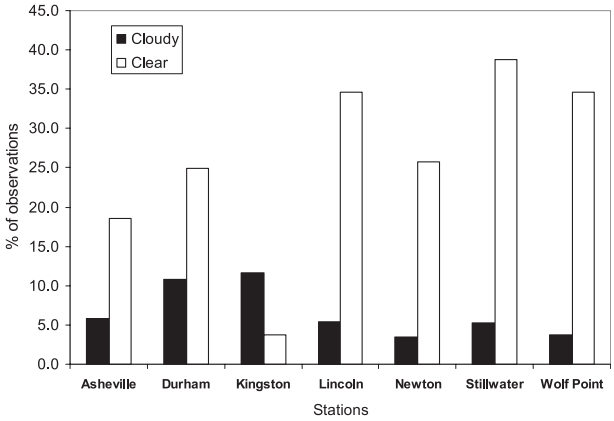

FIG. 1. Frequency of clear- and cloudy-sky observations for each of the stations.

amounts to determine clear-sky conditions. Had the clear-sky determination been based solely on the ratio of observed to theoretical maximum solar radiation, over 9000 observations would have been deemed clear at both Kingston stations, similar to the results observed for the other stations (Table 3). A histogram of sky cover observations for each of the stations of this study (Fig. 2) clearly demonstrates that the Kingston station displays markedly more frequent observations of few, scattered, and broken cloud cover than the other stations. Such fractions of cloud cover could result in both the high number of observations deemed clear by the solar radiation ratio method (since the pyranometer may receive direct solar radiation through any breaks in the clouds) and the low frequency of observations with a reported clear-sky cover.

The month-to-month variation in clear and cloudy observations was similar for all stations. Similar to the Lincoln, Nebraska, stations (Fig. 3), most stations displayed a greater frequency of clear-sky observations during the autumn months (September, October, and November) and displayed the least frequency of cloudy-sky observations during the summer months (June, July, and August). On a monthly basis, the number of clear or cloudy observations generally exceeded 1% of the potential number of observations. Only select months for Lincoln (July, 0.94%), Newton (May, 0.92%), and Wolf Point, Montana (July, 0.91%, and August, 0.96%), were found to be totally cloudy less than 1% of the daylight hours.

b. *LST and Tair relationship*

The mean difference observed between LST and Tair for all observation stations, as a function of local time of day, is displayed in Fig. 4a. A cyclic increase and decrease in the clear-sky hourly difference between LST and Tair generally follows the daily cycle of hourly incident solar radiation. Standard deviation in the difference between LST and Tair also varied with hour of the day, with the greatest values (as great as 5.4°C) observed near local solar noon. Under cloudy conditions, however, the difference between LST and Tair is fairly stable throughout the day, as was standard deviation in the difference (<1.4°C). Similarly, when displayed as a function of day of the year (Fig. 4b), the clear-sky mean difference between LST and Tair follows the cycle of incident daily radiation. The LST and Tair difference under cloudy conditions, as in the hourly example, is fairly consistent over the year.

TABLE 3. Number of clear and cloudy observations for each pair of stations for the 2003–08 study interval as determined by criteria presented in Table 2.

	No. of obs	
Station pair	Clear	Cloudy
Asheville	4603	1451
Durham	6135	2671
Kingston	917	2879
Lincoln	8665	1360
Newton	6401	862
Stillwater	9623	1299
Wolf Point	8550	923

An examination of the mean differences between LST and Tair for the pairs of stations indicates that, generally, LST is greater than Tair for both clear-sky and cloudy conditions, although the amount of the differences varies between the stations. While there are individual observations where Tair is greater than LST, the mean difference between LST and Tair for clear-sky conditions (Table 4) ranged from 2.58°C (Kingston 1W) to as great as 7.62°C (Asheville, North Carolina, 8SSW station). The mean differences between LST and Tair for the cloudy-sky conditions were less than the clear-sky conditions for all stations and ranged from a mean difference of 0.74°C (Durham, New Hampshire, 2N) to 1.81°C (Asheville 8SSW and Wolf Point 34NE). The 95% confidence intervals associated with the mean differences (not shown) indicate that less than a 2°C difference would be expected between LST and Tair under cloudy conditions for any of the stations, compared to a minimum difference of greater than 2°C (and as great as 7+°C) for the clear-sky conditions. The difference between LST and Tair additionally decreased when the cloudy-sky conditions were further differentiated by those observations that included observed precipitation (Table 4).

The differences in LST and Tair for the individual stations (e.g., the 7.62°C mean difference for Asheville 8SSW; Table 4) were significant for all stations for both

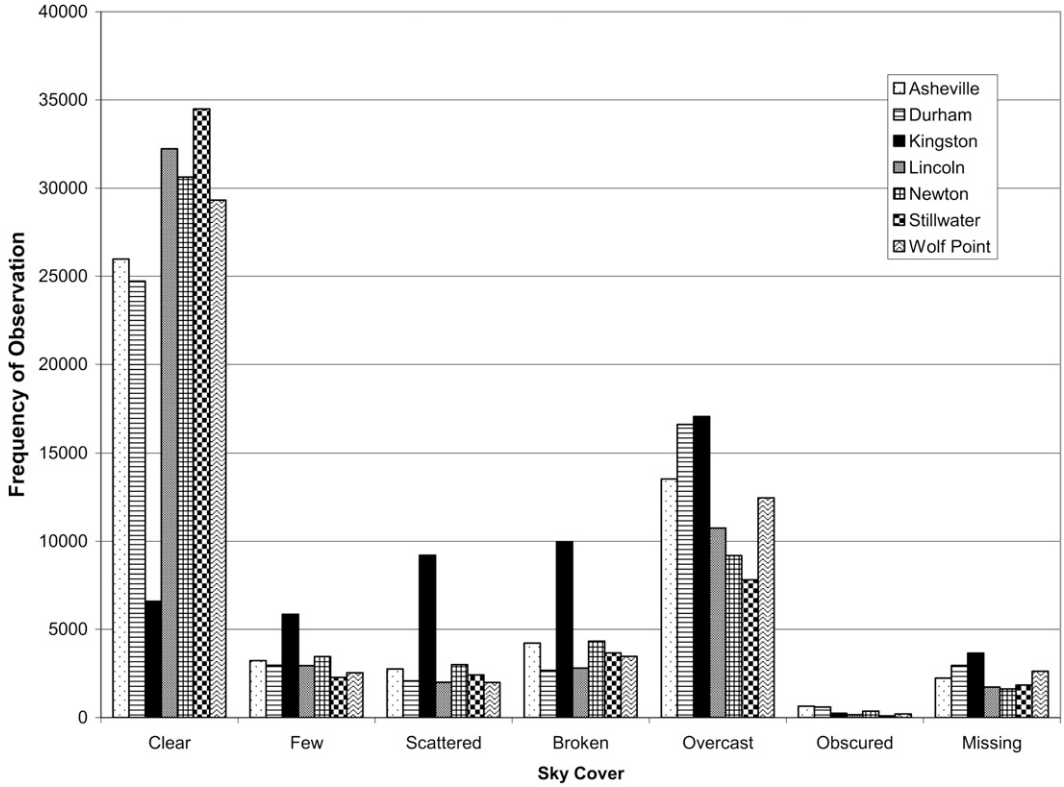

FIG. 2. Frequency of observations for stations included in this study based on sky cover.

clear and cloudy conditions. Additional analysis determined that for all stations, the clear-sky LST and Tair differences were significantly different from the corresponding cloudy-sky differences (e.g., the 7.6°C clear-sky difference in LST and Tair for Asheville 8SSW was significantly different from the 1.8°C cloudy-sky value for the same station).

The mean differences in the LST and Tair were also compared between the pairs of USCRN stations for the clear and cloudy conditions. The paired *t*-test analysis determined that the observed differences in LST and Tair (e.g., clear-sky mean values of 7.6 and 7.3 for Asheville 8SSW and 13S, respectively) were significantly different. The LST and Tair differences were significantly different between all pairs of stations, for both clear and cloudy observations.

In an effort to further evaluate the factors that might contribute to the observed variation in LST, an analysis of the variance in LST for each station—separated into clear and cloudy conditions—was conducted that included Tair, wind speed, season, and local hour of the day. Seasons were defined as winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November). Tair was a significant factor (p value = 0.01) for all stations for both clear and cloudy conditions. While wind speed, season, and hour of the day were significant factors for some of the stations, their contribution to explaining the variation in LST was minimal (generally less than 1%) in comparison with Tair (greater than 94% for cloudy-sky conditions). Based on the results of

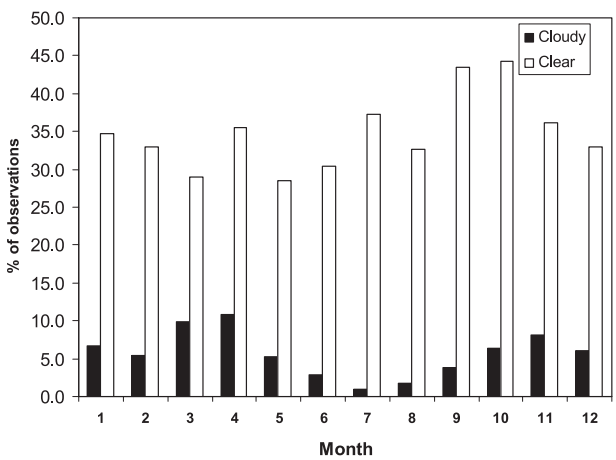

FIG. 3. Frequency of clear- and cloudy-sky observations by month for the Lincoln stations.

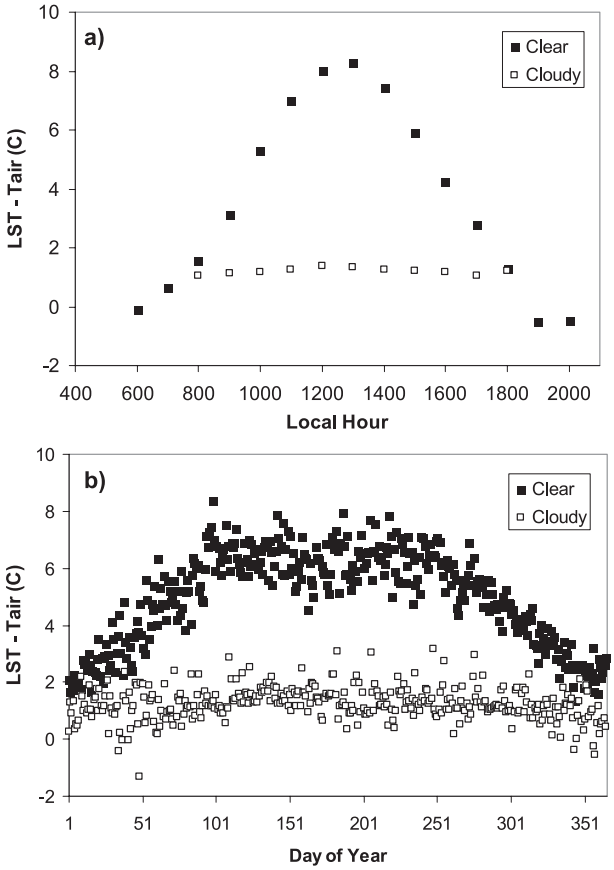

FIG. 4. Mean difference between LST and Tair (°C) for all stations displayed by (a) local hour and (b) day of year.

the analysis of variance, the relationship between LST and Tair was examined further in this study.

The relationships between LST and Tair for the Lincoln 11SW station for both clear and cloudy conditions are displayed in Fig. 5. A considerably greater amount of scatter exists for the clear conditions (Fig. 5a) compared to cloudy conditions (Fig. 5b), as might be expected because of the daily and annual differences in LST and Tair (e.g., Fig. 4). The least squares linear relationship [Eq. (1)] between LST and Tair is also displayed in Fig. 5, where b_0 is the intercept and b_1 is the slope:

$$\mathrm{LST} = b_0 + b_1 \mathrm{Tair}. \tag{1}$$

The greater scatter (variation in LST values for given values of Tair) for the clear condition observations is conveyed in the lower coefficient of determination (r^2) computed for the clear (relative to cloudy) conditions (Fig. 5). Additionally, the RMSE values associated with the cloudy-sky conditions were 4°C less than the value for the clear-sky conditions (Fig. 5).

TABLE 4. Mean ($\bar{x}$) and standard error (se) for observed differences between LST and Tair for clear- and cloudy-sky conditions.

	LST−Tair (°C)					
	Clear		Cloudy*		Cloudy**	
Station	$\bar{x}$	se	$\bar{x}$	se	$\bar{x}$	se
Asheville 8SSW	7.62	0.06	1.82	0.04	1.37	0.06
Asheville 13S	7.31	0.06	1.36	0.03	1.03	0.05
Durham 2N	3.04	0.04	0.74	0.02	0.44	0.03
Durham 2SSW	3.52	0.05	0.98	0.02	0.63	0.04
Kingston 1NW	3.85	0.13	1.18	0.02	0.60	0.03
Kingston 1W	2.58	0.11	0.89	0.02	0.65	0.03
Lincoln 11SW	4.88	0.06	1.58	0.03	0.95	0.04
Lincoln 8ENE	5.19	0.05	1.50	0.04	0.73	0.04
Newton 8W	6.17	0.04	1.27	0.04	0.63	0.04
Newton 11SW	6.60	0.06	1.62	0.05	0.94	0.06
Stillwater 2W	4.58	0.04	1.48	0.04	0.92	0.05
Stillwater 5WNW	4.16	0.05	1.37	0.03	0.86	0.04
Wolf Point 34NE	5.92	0.07	1.80	0.04	1.40	0.06
Wolf Point 29ENE	4.93	0.06	1.32	0.03	1.07	0.05

* All cloudy-sky observations.
** Cloudy-sky observations with occurrence of precipitation.

Similar results were observed for the clear and cloudy observations of the Lincoln 8ENE station, as well as the other stations (Table 5). These results were similarly observed in the r^2 and RMSE values from the analyses of clear and cloudy observations of LST and Tair for the other stations (Table 5). Thus, while other factors (e.g., wind speed) may contribute to the variation in LST (and at a greater level for the clear-sky conditions), Tair alone explains over 94% of the variation observed in LST under cloudy conditions. Additionally, the estimation of LST with Tair resulted in RMSE values less than 2°C for the cloudy-sky conditions, as compared with as great as 5.5°C for the clear-sky conditions. When data for all stations were combined, Tair explained over 88% and 97% of the variation in LST for the clear- and cloudy-sky conditions, respectively (Table 5).

The intercept b_0 and slope b_1 associated with the linear relationships between LST and Tair [Eq. (1)] for the individual stations are presented in Table 6. The intercepts for both clear- and cloudy-sky conditions were all significantly different from 0.0, and the slopes were all significantly different from 1.0 for the clear-sky condition relationships. Several of the cloudy-sky relationships (Asheville, Newton 8°W, and Wolf Point), however, exhibited slopes equal to 1.0. The slope of the relationship between LST and Tair was clearly closer to 1.0 for the observations during the cloudy-sky conditions compared to the clear-sky conditions. When data for all stations were combined, the slope of the relationship for the cloudy-sky conditions was not significantly different from 1.0 (standard error of 0.002).

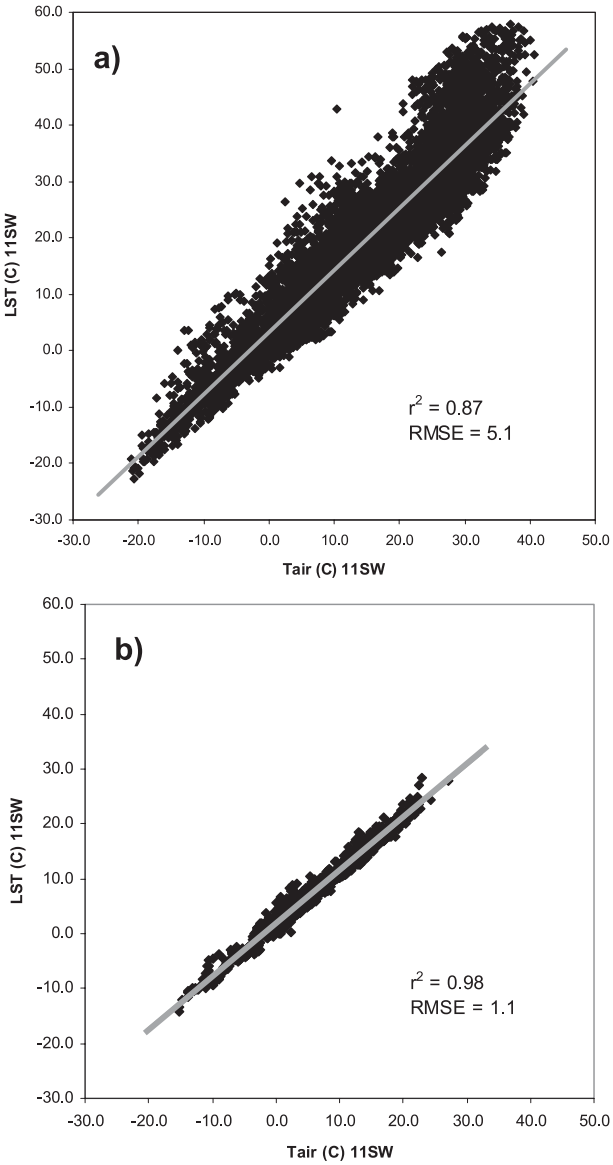

FIG. 5. Relationship between LST and Tair (°C) for Lincoln station 11SW for (a) clear-sky and (b) cloudy-sky observations. Linear regression relationship (gray line), r^2, and RMSE values are included.

TABLE 5. Coefficient of determination (r^2) and RMSE values that resulted from linear regression analysis of LST and Tair observations for clear- and cloudy-sky conditions.

Station	Clear		Cloudy	
	r^2	RMSE	r^2	RMSE
Asheville 8SSW	0.83	3.9	0.94	1.5
Asheville 13S	0.82	4.2	0.96	1.2
Durham 2N	0.93	3.5	0.97	1.2
Durham 2SSW	0.92	3.8	0.97	1.3
Kingston 1NW	0.89	3.8	0.97	1.3
Kingston 1W	0.91	3.4	0.98	1.1
Lincoln 11SW	0.87	5.1	0.98	1.1
Lincoln 8ENE	0.87	4.9	0.97	1.3
Newton 8W	0.90	3.2	0.96	1.2
Newton 11SW	0.81	4.8	0.95	1.3
Stillwater 2W	0.90	3.9	0.97	1.4
Stillwater 5WNW	0.88	4.4	0.98	1.1
Wolf Point 34NE	0.89	5.5	0.97	1.3
Wolf Point 29ENE	0.93	4.5	0.98	1.0
All stations	0.88	5.0	0.97	1.3

c. *LST and NDVI relationship*

One variable that might influence a portion of the variation in the clear-sky relationship between LST and Tair that is not routinely observed at the USCRN stations is the amount of green vegetation. The presence and density of green vegetation as indicated by the normalized difference vegetation index (NDVI) has been found to explain observed variations in LST in numerous studies (e.g., Prihodko and Goward 1997), although there is evidence that the commonly observed inverse relationship of decreased LST with increased levels of NDVI is not as common as often assumed (Karnieli et al. 2010). A cursory examination of the potential influence of vegetation on the relationship between LST and Tair included NDVI data available from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC 2010) that is derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the *Terra* platform. The mean 16-day composited NDVI values were obtained for 2.6×2.6 km^2 regions centered on the USCRN stations included in this study when greater than 80% of the land cover within the region was similar. Seven of the stations (Asheville 8SSW, both Lincoln stations, Newton 11SW, Stillwater 5WNW, and both Wolf Point stations; Table 1) met the required land cover threshold of 80% as determined from the MODIS-derived land cover data (also available from the ORNL DAAC). Tair and LST values were averaged over the 16-day intervals of the NDVI data for this analysis. Although linear relationships were observed between LST and NDVI, Tair explained all but a fraction of the variation in LST. Greater than 96% of the variation in LST was associated with the variation in Tair for the seven stations examined. The r^2 values differed slightly from those in Table 5 because of different sample sizes required to match the available NDVI data. NDVI was a significant factor in the relationship between LST and Tair for four of the cloudy-sky observations; however, it contributed to only a minor (<0.05%) portion of the overall explanation of the observed variation in LST when Tair was included in the analysis. NDVI was also a significant factor for four of the seven stations for the clear-sky observations; however, it also contributed to only a minor (as great as

TABLE 6. Intercept (b_0) and slope (b_1) values that resulted from linear regression analysis of LST (dependent variable) and Tair observations for clear- and cloudy-sky conditions.

Station	Clear				Cloudy			
	b_0*	se	b_1**	se	b_0*	se	b_1**	se
Asheville 8SSW	**6.26**	0.13	**1.08**	0.01	**1.68**	0.08	1.01	0.01
Asheville 13S	**5.86**	0.13	**1.09**	0.01	**1.33**	0.07	1.00	0.00
Durham 2N	**2.22**	0.06	**1.07**	0.00	**0.57**	0.04	**1.02**	0.00
Durham 2SSW	**1.88**	0.07	**1.15**	0.00	**0.67**	0.04	**1.03**	0.00
Kingston 1NW	**3.02**	0.17	**1.08**	0.01	**0.85**	0.05	**1.03**	0.00
Kingston 1W	**1.86**	0.15	**1.07**	0.01	**0.61**	0.04	**1.02**	0.00
Lincoln 11SW	**3.20**	0.09	**1.10**	0.00	**1.86**	0.04	**0.96**	0.00
Lincoln 8ENE	**4.11**	0.09	**1.07**	0.00	**1.68**	0.05	**0.98**	0.00
Newton 8W	**2.82**	0.10	**1.18**	0.00	**1.46**	0.11	0.99	0.01
Newton 11SW	**1.99**	0.15	**1.25**	0.01	**2.47**	0.13	**0.95**	0.01
Stillwater 2W	**2.01**	0.08	**1.13**	0.00	**1.82**	0.06	**0.96**	0.00
Stillwater 5WNW	**2.09**	0.09	**1.11**	0.00	**1.79**	0.05	**0.96**	0.00
Wolf Point 34NE	**2.79**	0.08	**1.24**	0.00	**1.76**	0.05	1.01	0.01
Wolf Point 29ENE	**2.45**	0.07	**1.18**	0.00	**1.36**	0.04	0.99	0.00
All stations	**2.82**	0.04	**1.15**	0.00	**1.33**	0.02	1.00	0.00

* Boldface indicates significant difference for test Ho: $b_0 = 0$ at p value <0.01.

** Boldface indicates significant difference for test Ho: $b_1 = 1$ at p value <0.01.

1%) portion of the overall explanation of the observed variation in LST when Tair was included in the analysis. A similar analysis of the relationship of LST, Tair, and NDVI with data that are more similar in spatial and temporal resolutions (e.g., Wilson and Meyers 2007) is recommended.

4. Conclusions

Although Tair is recognized as generally dependent on LST, the estimation of LST from Tair under cloudy conditions may be feasible. The results indicate that under cloudy conditions Tair alone explained over 94%—and as great as 98%—of the variance observed in LST for the stations included in this analysis. Thus, estimation of LST under cloudy-sky conditions may be feasible where Tair observations are available. The results suggest that the relationship between LST and Tair, even under cloudy conditions, can vary with location and thus will require a locally developed relationship. A portion of the unexplained variation in the relationship between LST and Tair may be attributed to soil moisture, although it would be less of a factor in the relationship between LST and Tair under cloudy-sky (relative to clear-sky) conditions. Observations of soil moisture are being added to the USCRN stations but were not consistently available for this analysis. Additional analysis of the relationship between LST and Tair are recommended as soil moisture data become available for the USCRN stations. The results of this study suggests that in situ data, as those available from the USCRN stations, may provide supplemental data for use in microwave-based retrievals of near-surface air temperature and LST, in addition to applications for thermal infrared sensor detection of LST. For an operational estimation of cloudy-sky LST at a pixel scale of 1–2 km, in addition to Tair data, additional land cover, emissivity, and topographic data would likely be required as well as soil moisture status. Future analysis that includes additional USCRN stations is recommended for evaluation of regional differences in the observed LST and Tair relationships. Additionally, because of the relatively homogeneous land surface characteristics encouraged in the immediate vicinity of USCRN stations, additional analysis of the relationships between LST and Tair for additional land surface conditions are recommended.

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