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Vegetation greenness impacts on maximum and minimum temperatures in northeast Colorado

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The impact of vegetation on the microclimate has not been adequately considered in the analysis of temperature forecasting and modelling. To fill part of this gap, the following study was undertaken.

A daily 850–700 mb layer mean temperature, computed from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis, and satellite-derived greenness values, as defined by NDVI (Normalised Difference Vegetation Index), were correlated with surface maximum and minimum temperatures at six sites in northeast Colorado for the years 1989–98. The NDVI values, representing landscape greenness, act as a proxy for latent heat partitioning via transpiration. These sites encompass a wide array of environments, from irrigated-urban to short-grass prairie. The explained variance (r^2 value) of surface maximum and minimum temperature by only the 850–700 mb layer mean temperature was subtracted from the corresponding explained variance by the 850–700 mb layer mean temperature and NDVI values. The subtraction shows that by including NDVI values in the analysis, the r^2 values, and thus the degree of explanation of the surface temperatures, increase by a mean of 6% for the maxima and 8% for the minima over the period March–October. At most sites, there is a seasonal dependence in the explained variance of the maximum temperatures because of the seasonal cycle of plant growth and senescence. Between individual sites, the highest increase in explained variance occurred at the site with the least amount of anthropogenic influence. This work suggests the vegetation state needs to be included as a factor in surface temperature forecasting, numerical modeling, and climate change assessments.

1. Introduction

Vegetation has transpirational and evaporational influences in the area it inhabits, affecting the surface energy budget. The presence of vegetation, as compared to bare soil, modulates the diurnal temperature cycle. During the day, transpiring vegetation partitions a greater portion of the incoming solar energy into latent heat, decreasing the maximum temperature. At night, the vegetated area radiates energy and allows condensation, increasing the minimum temperatures via latent heat release.

The region of focus in this study is northeast Colorado. This region is characterised by a mix of short grass steppe, urban and rural areas, and croplands. The Platte River Valley provides only a limited natural moisture source for increased humidity in the atmosphere – a more important moisture source is irrigation. The sites in this study encompass a wide array of environments, from pristine to mixed impact to heavily anthropogenically influenced (see Figure 1). Located in a rainshadow east of the Rockies, these locations generally receive 355–457 mm of rain annually and experience annual average maximum and minimum temperatures of 17.8 °C and 2.2 °C, respectively.

The purpose of this work is to determine if there is an increase in the explanation of the surface temperature maxima and minima by including vegetation greenness in the analysis. Previous studies of the temperature regime in eastern Colorado include Kittel (1990), Segal *et al.* (1988, 1989), Stohlgren *et al.* (1998), Chase *et al.* (1999), Doesken (2000) and Pielke et al. (2002).

2. Study sites

2.1 National Land–Cover Data

A cooperative effort between the US Geological Survey (USGS) and the US Environmental Protection Agency (USEPA) produced a National Land Cover Data (NLCD) set based on 30-metre Landsat thematic mapper data. The predominant vegetation land-cover designations of the sites used in this work, as defined by NLCD, are as follows:

a. Grasslands/herbaceous (71) – areas dominated by upland grasses and forbs. These areas are not subject to intensive management, but they are often utilised for grazing. (They are referred to in this work simply as 'grasslands'.)
b. Pasture/hay (81) – areas of grasses, legumes or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops. (They are referred to in this work simply as 'pasture'.)
c. Row crops (82) – areas used for the production of crops, such as corn, soybeans and vegetables.
d. Small grains (83) – areas used for the production of graminoid crops such as wheat, barley and oats.

2.2 Site designations

Five site designations were created to better classify and explain the varied results from the sites utilised for this work. A Type 1 site is considered pristine, with little or no anthropogenic influences. Type 2 is designated pristine-rural because the sensor is in a location that has some anthropogenic influence though surrounded by pristine-class landscape. Type 3 is designated rural, where the sensor is strongly influenced by anthropogenic factors though surrounded by pristine to pristine-rural landscape. Conversely, Type 4 is rural-urban, where the sensor location receives a strong vegetation influence though surrounded by urban character landscape. Urban is Type 5. It has almost no influence from vegetation and is completely dominated by the urban character. An example of a Type 5 site would be a sensor located on a low roof in a large city. Type 5 cases were not considered in this study. Table 1 shows a summary of these designations.

2.3 Surface metadata

Vegetation and land-surface characteristics of each site examined in this work were first detailed by the NLCD set (see Hanamean 2001). To discern temperature-impacting characteristics in the immediate vicinity, on-site inspections were made. These sites have been used in previous temperature-related studies (Pielke *et al.* 2000, 2002) and were considered appropriate for this work. Surface data used in this work were collected from the following northeast Colorado sites.

2.3.1 Akron 1N

Akron 1N (40°07′N latitude, 103°10′W longitude) is located at a municipal airport, approximately 8 m from the concrete aircraft apron and runway tarmac to the west (see Figure 2). Thirteen metres to the east is a dirt and gravel parking lot. Metal buildings stand 30 m and 16 m to the north and south, respectively. The landscape surrounding the immediate vicinity is dominated by grasslands in both the 1-km and 5-km radii of examination (see Hanamean 2001: Table A.1), with a strong residential/commercial presence to the south. Row crops and small grains exist in large swathes in the

Table 1. *Site category (type), designation, short description of site characteristics, example of this type used in this work, and the average increased r^2 value for the maximum and minimum temperatures, respectively*

Type	Designation	Description	Example	Average increased r^2 value (max/min)
1	Pristine	Very little to no anthropogenic influences	CPER	12.5/12.1
2	Pristine-Rural	Some anthropogenic influences though widely surrounded by pristine-class landscape	Akron 1N, Akron 4E	3.7/4.0
3	Rural	Strongly influenced by anthropogenic factors though widely surrounded by pristine to pristine-rural landscape	Fort Morgan, Wray	3.9/11.2
4	Rural-Urban	Receives strong influences from vegetation though widely surrounded by urban character landscape	Fort Collins	5.6/8.4
5	Urban	Almost no influence from vegetation, completely dominated by urban character	None in this work	5.6/8.4

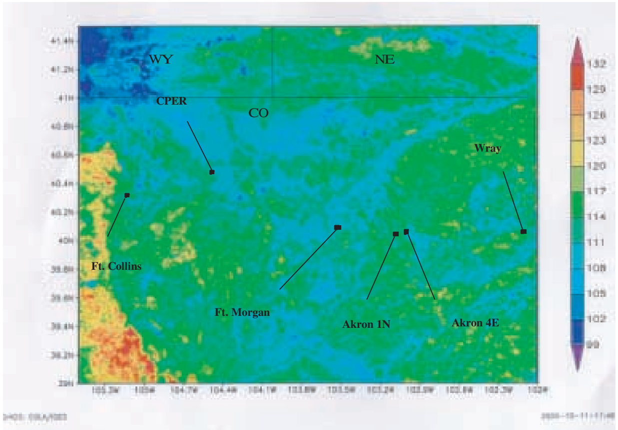

Figure 1. *Site locations in northeast Colorado superimposed on NDVI projection. The higher the NDVI value (right-hand scale), the greener (and more vegetated) the area.*

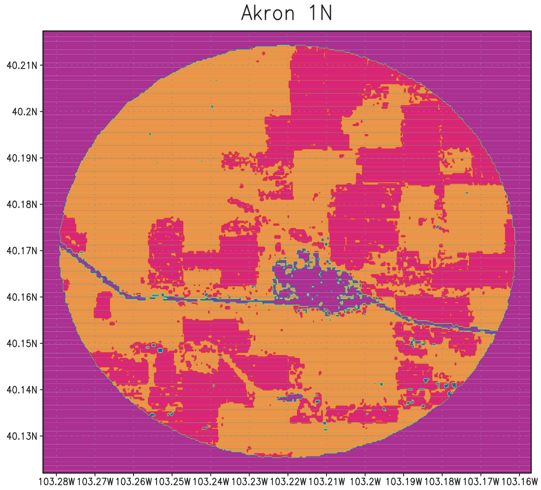

Figure 3. *5-km radius circle of 30 m resolution land-use data for Akron 1N. Purple = low and high intensity residential/ commercial/industrial/transportation; orange = grasslands/ herbaceous; dark red = herbaceous planted/cultivated. Other land use covers an area of less than 1%.*

southeastern two-thirds of the 5-km radius circle around the site (see Figure 3). Akron 1N is a Type 2 site.

2.3.2 Akron 4E

Akron 4E (40°09′N latitude, 103°09′W longitude) is located on grassland surrounded by row crops, with a general fallow/row crop mottling throughout the 5-km radius circle around the site (see Figure 5). Immediately surrounding the site (within 16 m) are irrigated corn and wheat fields. A single line of trees stand less than 1 km to the east (see Figure 4). Akron 4E is a Type 2 site, considered so because of the anthropogenic influence (large-scale irrigation) in the immediate vicinity.

2.3.3 Central Plains Experimental Range (CPER)

The 5-km radius circle around the site location (40°48′N latitude, 104°45′W longitude), is dominated by grasslands. Some small grain areas exist to the south and west. Of the sites examined, this one is considered the most natural or pristine and would probably have the highest impact of vegetation (see Figures 6 and 7). CPER is a Type 1 site.

Figure 2. *Akron 1N site, showing images of the cardinal directions from the sensor.*

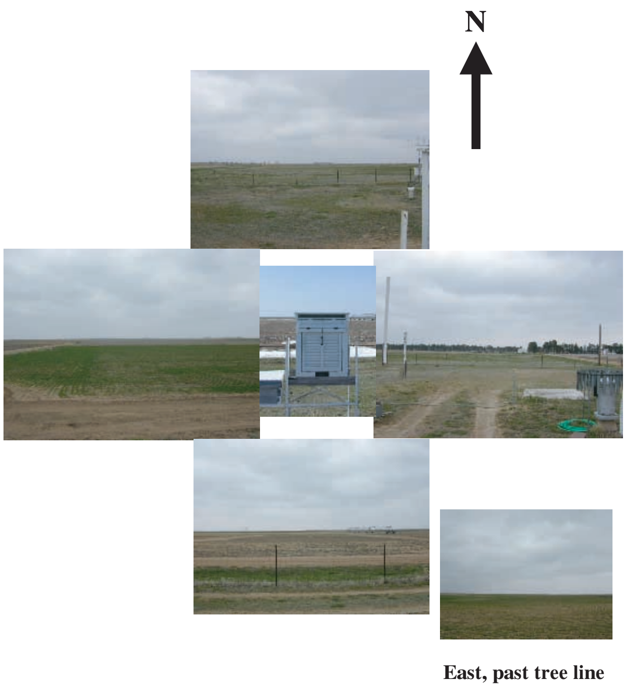

Figure 4. *Akron 4E site, showing images of the cardinal directions from the sensor.*

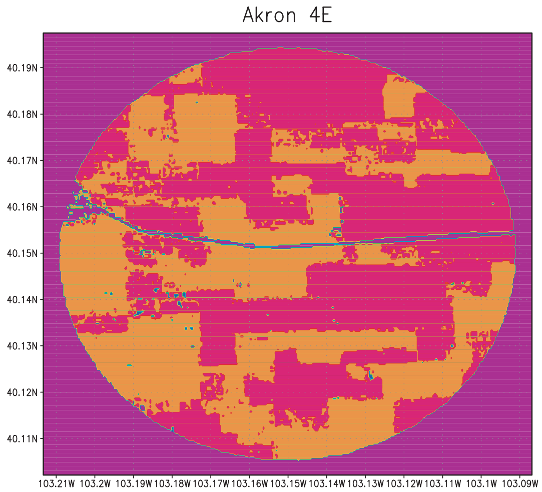

Figure 5. *5-km radius circle of 30 m resolution land-use data for Akron 4E. Purple = low and high intensity residential/commercial/industrial/transportation; orange = grasslands/herbaceous; dark red = herbaceous planted/cultivated. Other land use covers an area of less than 1%.*

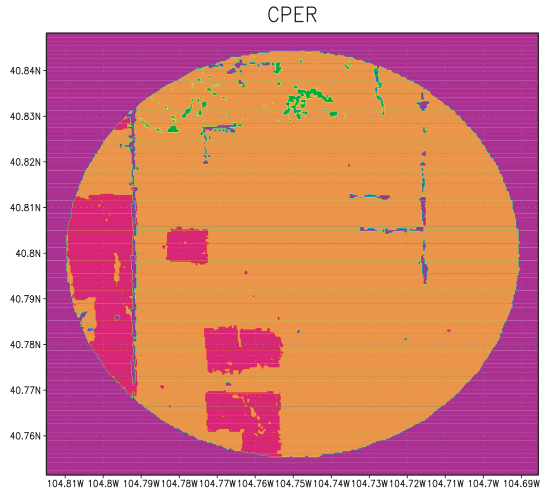

Figure 7. *5-km radius circle of 30 m resolution land-use data for CPER. Purple = low and high intensity residential/commercial/industrial/transportation; orange = grasslands/herbaceous; dark red = herbaceous planted/cultivated. Other land use covers an area of less than 1%.*

2.3.4 Fort Collins

The Fort Collins site (40°35′N latitude, 105°05′W longitude) is on the campus of Colorado State University and is immediately surrounded by short grass, a few trees and bushes, and a very large blacktop parking lot (see Figure 8). As a result of the trees and local urban character of the surrounding area, there is less wind at the Fort Collins site. Evaporation rates for this site reflect this lack of wind relative to the other sites. Large-scale irrigation, in the form of lawn maintenance, characterises the local landscape surrounding Fort Collins and adds a great deal of low-level moisture as well as enhanced greenness even through the more vegetation-stressing periods of July and August (see Figure 9). Fort Collins is a Type 4 site.

2.3.5 Fort Morgan

This site (40°16′N latitude, 103°48′W longitude), is surrounded by a mix of residential and commercial influences, grasslands, and row crops. The row crops and grasslands are dominant throughout the 5-km radius circle with the exception of the area to the immediate

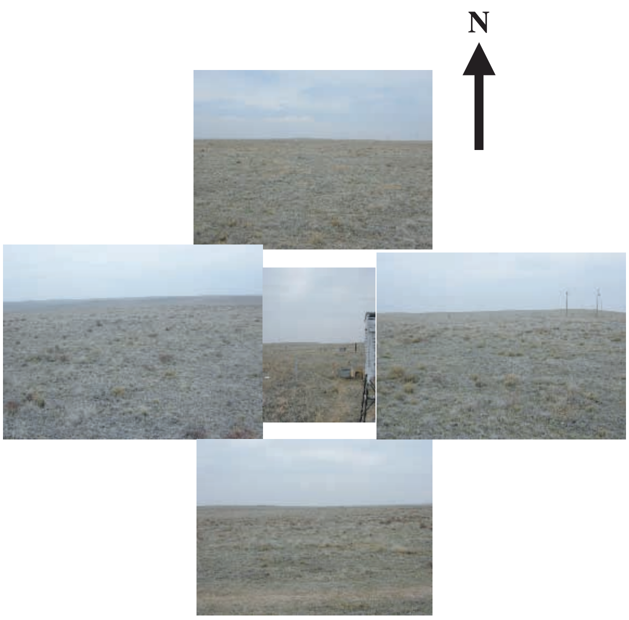

Figure 6. *CPER site, showing images of the cardinal directions from the sensor.*

Figure 8. *Fort Collins site, showing images of the cardinal directions from the sensor.*

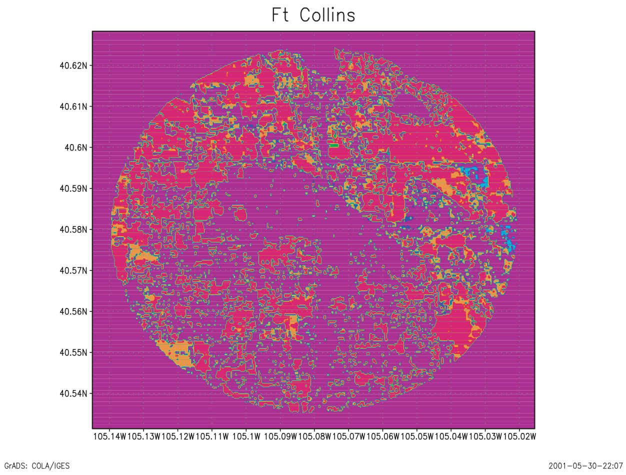

Figure 9. *5-km radius circle of 30 m resolution land-use data for Fort Collins. Purple = low and high intensity residential/commercial/industrial/transportation; orange = grasslands/herbaceous; dark red = herbaceous planted/cultivated. Other land use covers an area of less than 1%.*

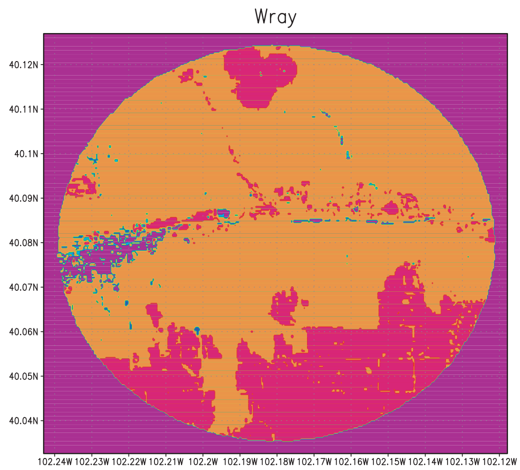

Figure 12. *5-km radius circle of 30 m resolution land-use data for Wray. Purple = low and high intensity residential/commercial/industrial/transportation; orange = grasslands/herbaceous; dark red = herbaceous planted/cultivated. Other land use covers an area of less than 1%.*

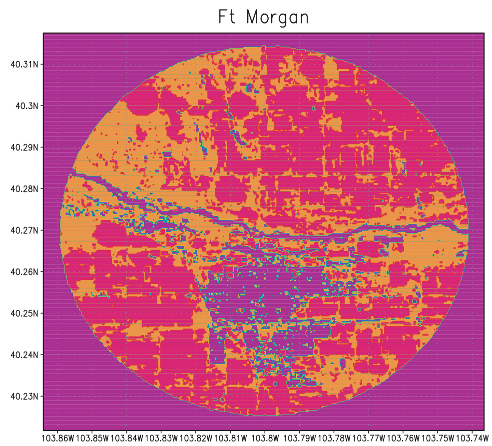

Figure 10. *5-km radius circle of 30 m resolution land-use data for Fort Morgan. Purple = low and high intensity residential/commercial/industrial/transportation; orange = grasslands/herbaceous; dark red = herbaceous planted/cultivated. Other land use covers an area of less than 1%.*

south where residential and commercial influences dominate (see Figure 10). The Platte River runs east-west approximately 1 km north of the site. However, the temperature sensor is located 3 m away from a large south-facing brick building, which is part of a much larger factory complex running east-west several hundred metres to either side (see Figure 11). The factory, which completely shields any northerly influence, has structures made of concrete and metal ranging from 3 to 7 storeys. Two and a half metres behind the temperature sensor is the exhaust of a window air conditioner. To the immediate south of the sensor is a dirt and gravel driveway. A small patch of grassy area extends from the gravel driveway out approximately 70 m but

Figure 11. *Fort Morgan site, showing images of the cardinal directions from the sensor.*

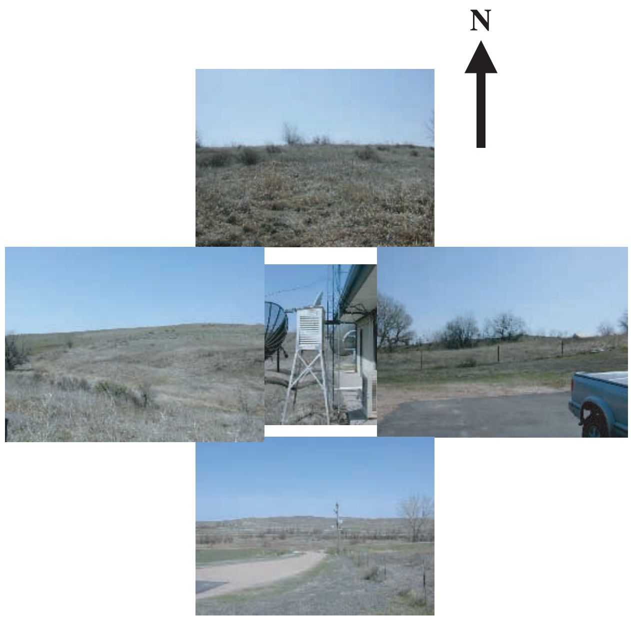

Figure 13. *Wray site, showing images of the cardinal directions from the sensor.*

there is a 4500 square metre dirt and gravel parking lot to its immediate west. Fort Morgan is a Type 3 site.

2.3.6 Wray

The Wray site (40°04′N latitude, 102°13′W longitude) is dominated by grasslands with small grains and fallow to the south and southeast, and north (see Figure 12). A residential/commercial area (the city of Wray) lies due west. The sensor is located 1 m from an aluminum-sided single storey building, and 0.75 m from a large air conditioning unit/evaporative cooling unit (see Figure 13). The sensor is on the south side of the building approximately halfway down a south-to-north-running slope. To the immediate west is a 10 m valley that could act as a drain for cooler air. The terrain immediately surrounding the site is hilly with higher elevations to the south. Wray is a Type 3 site.

2.4 Exposure differences

Although some of these sites have instrument exposures that are inappropriately located to measure accurately the predominant surrounding area, the fact is that these sites (and others like them) do exist and are used in collecting weather and climate data. As such, these sites are given unique classifications and grouped together appropriately. Both the Fort Morgan and Wray sites are specifically included in this study because of their poor exposures. Since the poor exposure remained consistent throughout the period examined, with only the vegetation greenness changing, the sites were viable for study. Type 3 sites are similar in nature to rooftop locations, which experience a temperature bias (Griffith 2000). The microclimate of the temperature sensor is impacted by the anthropogenic influence of the site exposure, though still mitigated in part by the larger surrounding environment. (Note: the Fort Morgan site has recently ceased operation.)

3. Data

3.1 Upper air data

National Centers for Environmental Prediction (NCEP)-National Center of Atmospheric Research (NCAR) reanalysis data at a 2.5° × 2.5° grid spacing were used for the 850 mb and 700 mb temperatures. The data were area averaged for a grid of 5 × 5 degrees (37°–42°N, 105°–100°W). The months of March through October for the years 1989–98 were extracted and used for this work. Reanalysis data were chosen over radiosonde data because of the spatial averaging over northeast Colorado that was required for the analysis. Radiosonde data were only available for two locations (Denver, Colorado and Goodland, Kansas), neither of which was representative of the sites under study. The radiosonde data were deemed too location-specific to be utilised for broader area averaging required in this work. Further, the reanalysis lent itself to the area averaging and gave more representative values of the 850 mb and 700 mb temperatures over the sites under study. Reanalysis data have been used for many studies, especially in the continental United States, and are considered reliable (e.g. see Kistler et al. 2001). The 0 UTC (18 local) temperature values are consistently the highest of the four times (0, 6, 12, 18 UTC) at the 850 mb level, indicating the general maximum temperature time (see Hanamean 2001: Fig. 3.1). Likewise, the 12 UTC (06 local) temperature values are consistently the lowest of the measurements taken at the four times. At the 700 mb level, there is very little variance between the temperatures taken at the four time periods (Hanamean 2001: Fig. 3.2). The 850–700 mb layer mean temperatures mirror the 850 mb results with 0 UTC (18 local) being the time of the temperature maximum and 12 UTC being the time of the temperature minimum (Hanamean 2001: Fig. 3.3). Since each 0 UTC temperature actually occurred during the previous evening, at 18 local time (local for northeast Colorado is UTC minus 6 hours), the maximum temperatures were appropriately shifted in the data set. The daily 850–700 mb layer mean maximum and minimum temperatures were calculated with a simple linear averaging. There was consistency in each site's temperature measurements, each site utilising either a liquid in glass thermometer or a maximum/minimum temperature sensor throughout the period studied. Since all temperature comparisons were made utilising the differences between measurements taken at the one site compared to the differences in measurements taken at the other site, there are no instrument issues to be considered.

3.2 Surface data

3.2.1 Surface temperatures

The surface temperatures were extracted from the Colorado Climate Center database and the CPER database, based on daily observational measurements. Four sites – Akron 4E, CPER, Fort Morgan and Wray – took their observations at 0700 local time. The maximum temperature recordings were therefore from the previous day. The maximum surface temperatures were appropriately shifted in the data set. The minima were not altered. The remaining two sites – Akron 1N and Fort Collins – took their observations in the evening. The maximum and minimum temperatures recorded were for that day. Thus, no adjustments were required for the data sets from these sites. All temperatures were converted to the Kelvin scale to eliminate negative temperature values in the calculations.

3.2.2 Precipitation

Precipitation data for all sites except CPER were retrieved from the Colorado Climate Center website.

CPER data were retrieved from the Natural Resource Ecology Laboratory (NREL) website under the SLIK–ECO download page. (SLIK–ECO is a project combining a collection of models, the Soil Water Model, the Ecotone Model, and the Century Model.) For all sites, missing precipitation measurements were given a value of zero for that day. These data were used in section 4.2.

3.2.3 *Evaporation rates*

The evaporation rates were culled from the National Oceanic and Atmospheric Administration (NOAA) Technical Report NWS 34 (Farnsworth & Thompson 1982) and from the Colorado Climate Center. The monthly climatological evaporation amount for each month, using pan evaporation data, was divided by the number of days in that month to arrive at an estimated daily evaporation value (Table 3). Akron 1N, Fort Morgan, CPER and Wray did not have on-site pan evaporation measurements. Pan evaporation measurements from other sites were used for the values of these four sites, taking into account geographic proximity and site similarity. Akron 1N and Akron 4E both used Akron 4E evaporation data. Fort Morgan and CPER utilised the evaporation data from the Wiggins site. Wray was assigned values averaged between Akron 4E and Bonny Dam. Fort Collins had its own evaporation data and was used for that site. The John Martin Dam site was similar to both Akron 4E and Bonny Dam. The March evaporation rates at John Martin Dam were used for the missing March data at all sites utilising Akron 4E and Bonny Dam data. Because of the general similarities of the rainfall patterns and the site locations between Wiggins and John Martin Dam, Fort Collins and CPER (which utilised Wiggins data) likewise took John Martin Dam March evaporation values for their missing March values. These data were used in section 4.2.

3.3 Normalised Difference Vegetation Index (NDVI)

The landscape greenness, represented by NDVI values, is used as a surrogate for the degree of latent heat partitioning via transpiration. NDVI is derived from data collected by the Advanced Very High Resolution Radiometer (AVHRR) sensor on NOAA satellites. Digital counts received by channels 1 and 2 of the AVHRR sensor are converted into radiances, normalised for the solar flux at the top of the atmosphere in the bands 0.5–0.7 micrometres and 0.7–1.3 micrometres, respectively. Channel 1, which measures radiance values in the visible spectrum, and channel 2, which measures radiance values in the near-infrared, of the sensor are ingested and the NDVI is calculated as follows: NDVI = (NIR – VIS) / (NIR + VIS). VIS and NIR refer to the normalised radiance values of the visible spectrum in channel 1 and the near-infrared in channel 2, respectively. The magnitude of NDVI is indicative of the amount of vegetation and how green it is. This greenness value acts as a proxy for photosynthetic activity, which is the agent of latent heat flux partitioning. The pixel size of the data is 1 × 1 kilometers. The NDVI data were acquired from Dr Brad Reed at the EROS Data Center. The NDVI values were calculated every 14 days and indicate the maximum NDVI measurement during that two-week period. NDVI values were extracted for the six sites of interest, using the site latitude and longitude as the centre of the NDVI pixel. Where the site was not at the exact centre of a data pixel, the pixel centre nearest the exact latitude/longitude of the site was automatically extracted. A simple weighting scheme was used to interpolate values for the 13 days between measurements to give a comparative daily value. The weighting scheme is as follows:

$$[\mathrm{NDVI1}*((15 - \mathrm{day})/14)]+[\mathrm{NDVI2}*((\mathrm{day} - 1)/14)]$$

where NDVI1 and NDVI2 are two sequential 14-day NDVI values, and 'day' is the number of the days between the two measurements (the day of a measurement is 'day' = 1, the day before a measurement is 'day' = 14). Thus, the calculated value at day = 1 is the value of the measurement and has no weight from the next measurement value. The normal values of NDVI, which are –1 to 1, have been scaled to eliminate negative numbers. The following is the transformation equation:

$$[(\mathrm{NDVI}*100)+100] = \text{Scaled NDVI Value}$$

The scaled NDVI values range from 0 to 200.

4. Methodology

4.1 Data format and statistics

Several basic statistical concepts and operations were used for this work. The coefficient of determination, or r^2 value, is the ratio of the explained variance between two sets of measurement values. Multiplied by 100, the coefficient of determination becomes a percentage-explained variance, indicating what percentage of the change in one variable is predicted or explained by the change in another. For this work, the r^2 value, herein referred to as the explained variance, indicates the degree of explanation of the surface temperature maxima and minima by the 850–700 mb layer mean temperature maxima and minima with and without the inclusion of vegetation impacts via NDVI values. Subtracting the r^2 value without the inclusion of vegetation impacts from the value including those impacts results in an r^2 difference value. This difference value will show the change in explanation of the surface temperature extrema by inclusion of vegetation influences. Typical values for these variables are shown in Table 2.

Table 2. *A data table used in this work, showing the range of r^2 values for that site. The values in this table are, in general, indicative of the other sites studied. S = surface temperature, L = layer temperature (850–700 mb layer mean temperature) and N = NDVI. The SLN column, therefore, stands for the correlation (squared) between the surface temperature and the layer temperature with NDVI. The SL column is the same, except without the NDVI*

		MAX		MIN		MAX	MIN
		SLN	SL	SN	SLN	SLN–SL	SLN–SL
89	MA	0.3797	0.3803	0.8216	0.7784	–0.0006	0.0432
	MJ	0.251	0.2524	0.801	0.7483	–0.0014	0.0527
	JA	0.4681	0.4538	0.6783	0.6571	0.0143	0.0212
	SO	0.6376	0.6159	0.853	0.7917	0.0217	0.0613
90	MA	0.5406	0.475	0.8189	0.786	0.656	0.0329
	MJ	0.5799	0.5536	0.8607	0.8597	0.0263	0.001
	JA	0.5763	0.5416	0.4251	0.3276	0.0347	0.0975
	SO	0.4895	0.3793	0.8954	0.8489	0.1102	0.0465
91	MA	0.07821	0.05076	0.6995	0.6581	0.02745	0.0414
	MJ	0.7125	0.6397	0.6909	0.6892	0.0728	0.0017
	JA	0.4621	0.4419	0.5581	0.4286	0.0202	0.1295
	SO	0.3953	0.3929	0.8334	0.7036	0.0024	0.1298
92	MA	0.4604	0.4577	0.5688	0.5163	0.0027	0.0525
	MJ	0.5172	0.4999	0.6559	0.6539	0.0173	0.002
	JA	0.25	0.2552	0.774	0.6947	–0.0052	0.0793
	SO	0.3696	0.3366	0.7803	0.7711	0.033	0.0092
93	MA	0.4226	0.3188	0.7522	0.6758	0.1038	0.0764
	MJ	0.5558	0.5553	0.8796	0.8672	0.0005	0.0124
	JA	0.2013	0.1471	0.5942	0.573	0.0542	0.0212
	SO	0.2361	0.1783	0.7675	0.7662	0.0578	0.0013
94	MA	0.256	0.2263	0.8216	0.7799	0.0297	0.0417
	MJ	0.6291	0.6301	0.694	0.6797	–0.001	0.0143
	JA	0.3314	0.2394	0.2111	0.2116	0.092	–0.0005
	SO	0.7772	0.7602	0.9034	0.8873	0.017	0.0161
95	MA	0.3364	0.3336	0.7141	0.6829	0.0028	0.0312
	MJ	0.761	0.6656	0.869	0.8116	0.0954	0.0574
	JA	0.4341	0.4162	0.6151	0.5909	0.0179	0.0242
	SO	0.5251	0.4122	0.8522	0.7795	0.1129	0.0727
96	MA	0.2876	0.2742	0.7904	0.7754	0.0134	0.015
	MJ	0.4767	0.4606	0.8123	0.7566	0.0161	0.0557
	JA	0.5169	0.3079	0.2788	0.2115	0.209	0.0673
	SO	0.4921	0.4556	0.8393	0.7576	0.0365	0.0817
97	MA	0.217	0.2026	0.7994	0.7339	0.0144	0.0655
	MJ	0.4954	0.4958	0.8455	0.8453	–0.0004	0.0002
	JA	0.2259	0.2152	0.6209	0.576	0.0107	0.0449
	SO	0.6238	0.5194	0.7284	0.6618	0.1044	0.0666
98	MA	0.5559	0.5379	0.6216	0.6183	0.018	0.0033
	MJ	0.369	0.3587	0.6459	0.6445	0.0103	0.0014
	JA	0.631	0.6279	0.6028	0.5026	0.0031	0.1002
	SO	0.7667	0.702	0.9043	0.8762	0.0647	0.0281

The statistical software program S-Plus 2000 by MathSoft© was utilised to produce the multiple linear regressions for the analysis. The particular regression utility used was the Robust LTS (Least Trimmed Squares) method. According to S-Plus 4 Guide to Statistics (1997), the Robust LTS regression is a highly robust method for fitting a linear regression model. The LTS estimate β_{LTS} minimises the sum of the q smallest squared residuals

$$\sum_{i=1}^{q} r_{(i)}^2(\beta)$$

where $r_{(i)}(\beta)$ is the ith order residual. The value of q is often set to be slightly larger than half of n. By contrast, the ordinary least squares estimate minimises the sum of all of the squared residuals.

$$\sum_{i=1}^{n} r_{(i)}^2(\beta)$$

Robust regression complements classical least-squares techniques where the distribution errors do not satisfy normality conditions (i.e. the errors do not fit a normal distribution) or when the data contain significant out-

Table 3. *Average daily evaporation rates for the sites under study in inches. (Note: Ak1N uses Ak4E rates; FM and CPER use Wiggin's rates; Wray uses a Bonny Dam/Ak4E average. All but FC use John Martin Dam rate for March because of the similarity of their evaporation profiles and the missing March rates at these sites.)*

	EVAPORATION Rates (mm/day)							
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
Ak4E	4.3	6.9	7.6	9.6	10.9	9.4	7.6	5.1
CPER	4.3	6.1	7.1	7.4	8.4	6.9	5.1	3.6
FC	1.0	3.8	4.6	5.3	5.8	5.3	4.1	2.5
FM	4.3	6.1	7.1	7.4	8.4	6.9	5.1	3.6
Wray	4.3	6.1	7.4	9.4	10.2	8.9	6.9	4.8

liers. However, the robust regression results are very similar to classical least-squares regressions for normal error distributions. The data sets utilised were assumed to have non-normal error distributions.

4.2 Removal of days with precipitation

Precipitation events impact the temperature schemes, dramatically reducing the maximum and raising minimum surface temperatures at nearly every occurrence. Figure 14 shows the impact of all precipitation events that resulted in more than a trace amount over the period of study. To better isolate the impacts of the vegetation, the precipitation event days were removed from the analyzed data sets. Precipitation events that far exceeded the estimated daily evaporation rate for that month for that site (see Table 3) had the following day's data removed as well. This was to reduce the possibility that the degree of latent heat flux partitioning would be caused by the evaporation of standing water or excessively moist soil from the previous rain event instead of transpiration from the vegetation itself. The use of evaporation rates help to identify lingering effects of heavy precipitation events.

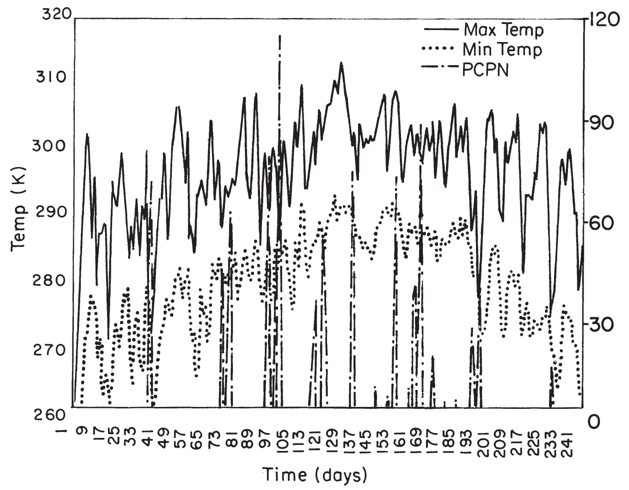

Figure 14. *Precipitation impacts on temperatures (Wray 89), shows how surface temperatures change in response to precipitation events. The Wray 89 depiction is representative of all sites and all years studied.*

4.3 Study period

The time-frame utilised for the data sets was March through October in the years 1989 to 1998. March is considered early or pre-spring and, in some instances, greening begins in this month. October was considered the end of summer and was included for completeness and comparative analysis. Further, regreening sometimes occurs in the natural landscape after the late summer senescent phase passes. The typical climatological evolution of rainfall in this region is a spring wet period followed by drier summer conditions (Cowie & McKee 1986; Pielke & Doesken 2003).

4.4 Analyses

First, the robust LTS regressions were performed for the time period extending from the March to October time frame excluding the precipitation event days, for each site for each year from 1989 to 1998. Second, the regressions were then performed over the same time periods broken into four two-month blocks of March–April, May–June, July–August and September–October to evaluate if a seasonal pattern was discernible. An analysis of statistical significance was then performed. All values that fell below the 95% confidence level ($p > 0.5$) were deleted from the analysis. Then the remaining r^2 values for the 850–700 mb layer mean and surface temperature analyses were subtracted from the r^2 values of the 850–700 mb layer mean with NDVI and surface temperature analyses (regressions without vegetation) for the temperature maxima and minima. This produced an r^2 difference value. For example, using values in Table 2, for 94MA (March–April 94) for the maximum temperature, the correlation between the maximum surface temperature, maximum layer temperature, and the NDVI value, produces an r^2 value of 0.256. The correlation between only the surface maximum temperature and the layer maximum temperature produces an r^2 value of 0.2263. The r^2 difference value then would be 0.256–0.2263, or 0.0297, or roughly a 3% difference in explained variance by including the vegetation greenness value in the correlation. Finally, at each site the four time-block r^2 difference values were each time-averaged over the years under study. For example, all the March–April Wray maximum temperature r^2 difference values were averaged over 1989 to 1998. This averaged r^2 difference value was then graphed and compared to the other time-block values for Wray and the other sites. The data deletions due to lack of statistical significance greatly impacted the CPER maximum temperature r^2 values, leaving only one value (i.e. one year's averaged values – 1995, a period of slow transition between a moderate El Niño and a weak La Niña event) to be averaged over the July–August time-block and three values (three years – 1989, a strong La Niña year, and 1992 and 1998, which had strong El Niño events) averaged for the March–April time-blocks. This is in contrast to the 7 to 10 years of data that were averaged for the other sites. The minimum temperature r^2 values at CPER were not affected significantly. Figures 15–16 for the maxima and Figures 17–18 for the minima show the difference in the 95% significance level compared to the raw data (no significance assessed).

5. Results

5.1 r^2 comparisons

As previously described, the final analysis performed was that of time-block averaged r^2 difference values for 1989 through 1998 at the 95% confidence level. Figures 15 and 17 display the results of these averaged r^2 difference values. For comparison, Figures 16 and 18 depict maximum and minimum r^2 difference values for all data regardless of statistical significance. The disparity between the different sites is immediately noticeable. However, it is significant that all the averaged r^2 difference values for all sites for both the maximum and minimum temperatures were positive. This implies that there is a consistent and significant improvement in explanation of surface temperature maxima and minima by including vegetation influences via the NDVI values. There were negative individual r^2 difference values for 28 out of 414 measurements, giving a 6.8% occurrence rate. However, of the 28 negative r^2 difference values not one was greater than 0.0023. No values explained more than 0.23% of the surface temperature variance. Figure 19 shows the comparison of magnitudes between one of the largest negative r^2 difference values (0.0022) and the rest of the values from that site. Clearly, the negative values lacked significant impact. On the other hand, 42 values had positive r^2 differences but were less than 0.5% and were likewise of negligible impact. This left 344 r^2 difference values that were positive and explained more than 0.5% of the variance in the surface temperature. These 344 values ranged from

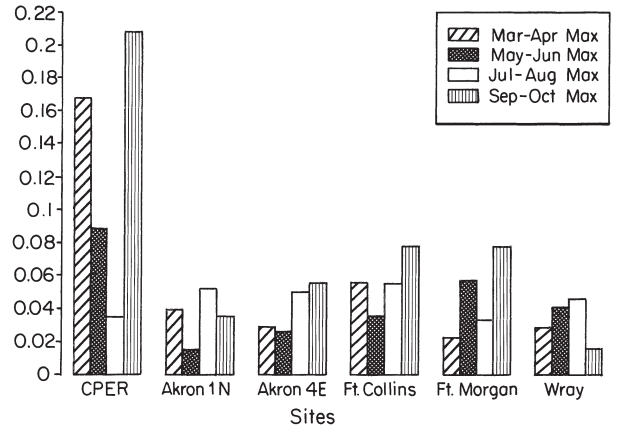

Figure 15. *Averaged r^2 differences. Time-blocks for the years 1989–1998. Maximum temperatures. Shows the r^2 difference between the 850–700 mb layer mean temperature maxima correlated to the surface temperature maxima subtracted from the same layer mean temperature extrema including vegetation impacts via NDVI values correlated to the surface temperature extrema. Values are significant to 95% confidence level.*

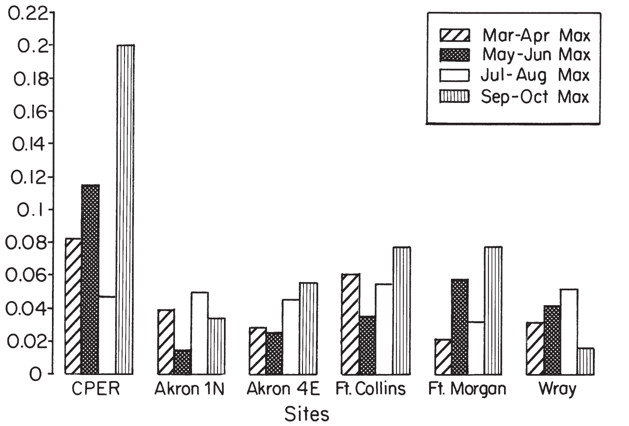

Figure 16. *Same as Figure 15 except all data was included prior to significance-test deletions for comparison.*

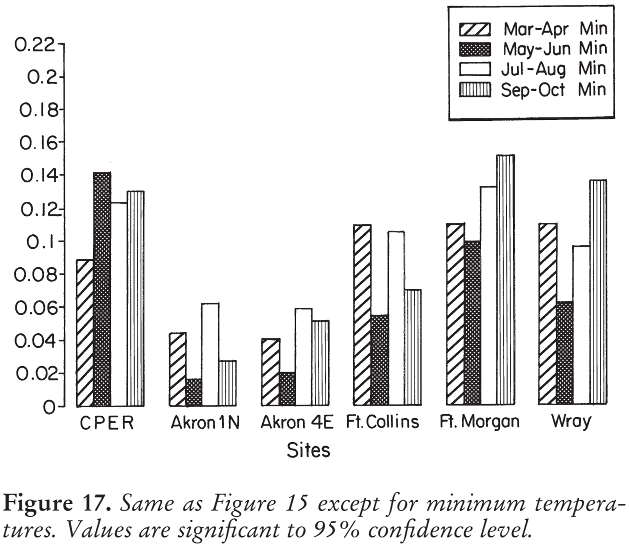

Figure 17. *Same as Figure 15 except for minimum temperatures. Values are significant to 95% confidence level.*

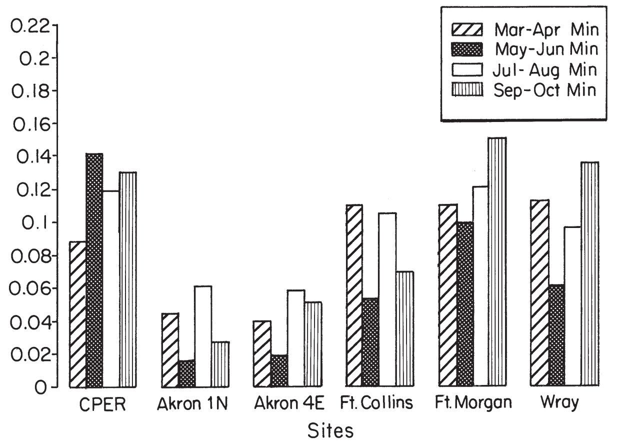

Figure 18. *Same as Figure 17 except all data were included prior to significance-test deletions for comparison.*

0.5 to an extreme of 52.24%. These greater r^2 difference values coincide with the greater averaged r^2 difference values in Figures 15 and 17. The r^2 difference values depict the difference in the explanation of the variance of the surface temperature maxima and minima because of the inclusion of vegetation influences. The averaged r^2 difference values ranged from 1.6 to 20.8 percent. Averaging these values produced a mean maximum surface temperature explained difference value of 5.6%, and a mean minimum surface temperature explained difference value of 8.5%. These explained difference values represent increases over the degree of explanation using the 850–700 mb layer mean temperature alone. These increases were in spite of mitigating impacts and factors from some of the sites and sensor locations. These mitigating influences are examined in even more detail in Hanamean (2001: Appendix C).

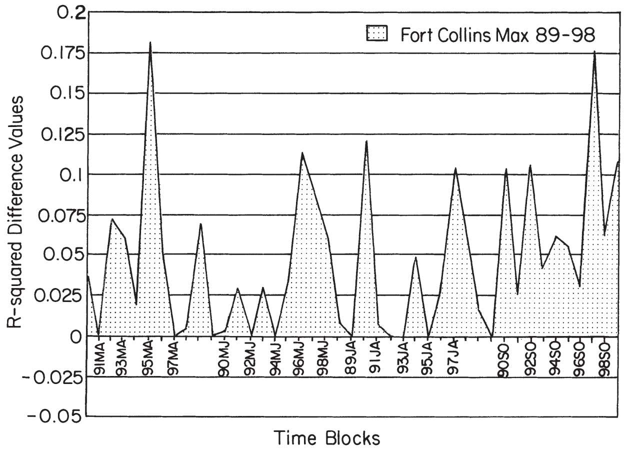

Figure 19. *r^2 difference values for maximum temperatures at Fort Collins for 1989–1998. The negative r^2 value of 0.0022 (one of the largest in this analysis) appears where the 93MJ mark is too small even to be visible.*

5.2 Diurnal variations

Distinct diurnal variations can be seen by comparing Figures 15 and 17. The magnitudes of the variations are driven by each site's microclimatic conditions. With one exception, vegetation had a greater impact on the minimum temperature than on the maximum temperature at every site. Type 3 sites had the greatest average differences, averaging 7.6% for Fort Morgan and 6.8% for Wray. Wray also held the greatest average diurnal extremes of 1.9 and 11.9%. At the other end of the spectrum, the Type 2 sites had the smallest average differences, averaging 0.2 and 0.4% for Akron 1N and Akron 4E, respectively. Akron 4E also had the smallest extremes of average diurnal difference values, ranging from 0.4 to 1.2%. Fort Collins, the Type 4 site, had an average diurnal difference of 2.8%, falling between the Type 2 and 3 site averages. CPER, the exception noted above, had an average diurnal difference of 0.4% greater explanation of the maximum temperatures over the minimum temperatures.

5.3 Site ranking

The thematic grouping, or ranking, according to site characteristics was shown in Table 1. To recap, of the five graduations considered, only four were utilised for this work. The spectrum ran from CPER, a pristine Type 1 site to Fort Collins, a rural-urban Type 4 site. The site maximum and minimum r^2 difference values were averaged across each type to give values indicative of the characteristics of that class. CPER, the most natural site with the least anthropogenic influences, had the greatest overall increase in explained variance for both day and night compared to the other type-averaged categories. (On a site-to-site comparison, Fort Morgan, a Type 3 site, had a slightly greater increase in explained variance for minimum temperatures (12.3%) over CPER (12.1%).) However, Fort Collins, the most urban and anthropogenically-influenced site, had a slightly greater maximum temperature average r^2 difference value than the Type 2 or Type 3 sites. The minimum temperature explained variance increase at Fort Collins was greater than the Type 2 sites but less than that of the Type 3 sites. The Type 2 and 3 sites had similar maximum temperature r^2 difference profiles. The corresponding minimum temperature profiles, however, show a marked difference between the two anthropogenic-influenced sensor sites and the two that had less anthropogenic influences.

The greatest average influences from vegetation are seen in the Type 1 environment, with an average r^2 increase of 12.5% for the maximum temperatures and 12.1% for the minimum temperatures. This Type 1 site was the only class where the average r^2 difference increase for the maximum temperatures was greater than that for the minimum temperatures. The smallest overall changes in surface temperature due to influences from vegetation occur in the pristine-rural Type 2 areas, showing an average of 3.7% increase for maxima and 4.0% for minima. This may be a result of extra latent heat fluxes from soil moistened by irrigation. Compared to Type 2, Type 3 sites have a nearly equal average daytime impact, increasing by an average of 3.9%. Comparatively, they have an increased nighttime influence from vegetation, averaging just below 11.2%. Type 4 average r^2 increases were 5.6% for maxima and 8.4% for minima.

6. Discussion and conclusions

There is definite and positive value added by the inclusion of vegetation parameters in the analysis of the surface temperatures. Among the conclusions, sensor location and placement are concerns and need to be addressed by the National Weather Service. The example of Fort Morgan, with its sensor 3 m from a north-shielding brick factory building, and 2.5 m from the exhaust of a window air conditioner, can only give temperature readings that are representative of that very isolated area. Wray is in a similar situation. The question of representativeness must be determined and appropriate placement action taken to avoid the skewing of temperature data. This is especially true of sites that are routinely used for climate studies.

There is a greater degree of explanation for the surface temperatures from the combination of 850–700 mb layer mean temperatures and NDVI values than for the 850–700 mb layer mean temperatures alone. With the exception of CPER, the minimum temperatures on average, are explained more by the inclusion of the NDVI data in the analysis than for the maximum temperatures for all other sites and for all years. The seasonal variations are quite pronounced and vary from site to site and can be explained in part by the location and the influences of the specific vegetation around each site.

As a result of these site–specific conditions, five categories were created to account for and better analyse the variations that occurred between the sites. The most pristine site, with the fewest anthropogenic influences, was found to have the greatest average increase in explained variance for both maximum and minimum surface temperatures. The inclusion of NDVI data in the analysis increases the percentage of explained variance for the maximum temperatures between 1.6% and 20.8%, with an average of 6%, and the minimum temperatures between 1.7% and 15.1%, with an average of 8%.

This would indicate that the inclusion of NDVI data could increase the predictability of maximum and minimum temperatures. Further study should be conducted at other sites to confirm these results. Future work should utilise a significantly larger sample size of sites that represent all five site categories (Brock *et al.* 1995; Brotzge & Crawford 2000). The ultimate goal is to derive a technique that adequately and accurately considers and ingests the vegetation impact in the analysis of the surface temperature extrema.

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