AVHRR estimates of surface temperature during the Southern Great Plains 1997 Experiment

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Abstract. In this study we aim to (1) explore the differences in the accuracy of satellite-derived land-surface skin temperature for day and nighttime observations, (2) assess the effects of large solar zenith angles, and (3) develop an understanding of the spatial variability of the observed temperatures. Land-surface skin temperatures are obtained using the split-window technique from observations of the AVHRR instrument aboard the NOAA-12 and NOAA-14 satellites for the SGP97 (Southern Great Plains 1997) hydrology experiment. From the study of several days of observations we find that observed biases with respect to the ground temperature, both during day and night, are small. However, except for one rainy day measurement, there consistently was a warm bias during the day and cold bias during the night. Contrary to the hypothesis that at large solar zenith angles the observed temperatures are representative of the shelter height air temperature, we find that the observed temperatures are still closer to the ground temperatures than the air temperature. The spatial correlation is nearly isotropic and has an exponential decay. The correlation lengths demonstrate tremendous spread both during the day and during the night with the mean during the day being about 50% larger than that during the night. The average correlation length of 8.63 km during the day is much smaller than the grid sizes typically used in short-time hydrology/mesoscale forecasts. This suggests that for modeling purposes the temperatures in each grid box may be treated as uncorrelated. However, the variance captured can be significantly smaller than the true value.

1. Introduction

The availability of satellite-based measurements of land-surface characteristics is providing a powerful avenue for investigating large-scale dynamics of hydrologic processes, especially those related to the land-atmosphere interaction. These observations not only are providing data for initializing and validating hydrologic models [Jin et al., 1997] for large-scale studies but are also increasingly being utilized in data-assimilation mode for improving the model forecast/prediction. Among the several parameters involved in such studies, surface temperature plays a crucial role in determining the partitioning of incoming radiant energy into the ground, sensible, and latent heat fluxes, and the determination of outgoing longwave flux. Recent studies [Lakshmi, 1998] have shown that assimilation of surface temperature can be used to improve the prediction of near-surface soil moisture. In order to guarantee that such studies are successful, it is important to understand the accuracy of the estimation techniques for the satellite-derived skin temperature, its relationship with the observed soil and air temperatures, and its spatial variation. This work is targeted toward this objective with the aim that an improved understanding of these factors will enable us to better utilize the data in modeling and simulation studies.

Given the numerous applications of surface temperature, its estimation using satellite observations [Price, 1984] has been the subject of several investigations for testing and improvement of retrieval algorithms, and understanding of factors influencing its variability. The most popular estimation method for land-surface temperature is a variant of the split-window technique developed for sea surface temperature [Price, 1984]. To apply this technique to land surface, corrections are applied to adjust for emissivities for different surface types. Several validation studies over different terrain types have indicated discrepancies ranging from 1 to 3 K. Price [1984] reported that with an emissivity correction the split-window technique used on an area of land in the south central United States gave an overall error of 2–3 K. Vidal [1991] found that the global error of the split-window technique combined with an emissivity correction over an area in Morocco was about 3 K with a 2 K difference from blackbody temperature estimation and a 1 K difference from emissivity errors of ~1%. Similarly, Ottlé and Vidal-Madjar [1992] reported that an error of 2% on the mean surface emissivity values yielded a difference of 1 K of the estimated surface temperature for a region in southwestern France. Schmugge and Schmidt [1998] reported a bias of 5 to 6 K in NOAA-9 advanced very high resolution radiometer (AVHRR) derived temperature estimates, as compared to infrared measurements at the ground, using a split-window technique, over the FIFE (First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment) site. In all the above studies, the satellite estimates were generally higher than the ground measurements.

This study examines the accuracy and spatial variability of skin surface temperatures derived from the AVHRR instrument aboard the NOAA-12 and NOAA-14 satellites for the SGP97 (Southern Great Plains 1997) hydrology experiment [Jackson, 1997] study site, with particular emphasis on understanding the differences between the day and nighttime estimates. SGP97 was a field experiment carried out in the sub-humid environment of Oklahoma from June 18 to July 17, 1997, to primarily investigate if retrieval algorithms for near-
surface soil-moisture developed earlier [Jackson et al., 1995] using an L-band electronically scanned thinned array radiometer (ESTAR) instrument aboard an aircraft can be extended to coarser resolutions expected from satellite platforms. Additional objectives of the experiment were to retrieve vertical profiles of soil-moisture and temperature using in situ and remote sensing data, along with modeling techniques, and to study their influence on the development of the boundary layer. Although the soil-moisture mapping domain consisted of an area of \(~10,000\ km^2\), we consider an area of about 5000 km\(^2\) centered over the Little Washita basin which was densely instrumented for in situ measurements. Land cover in the Little Washita watershed is primarily shrub, grassland, and cropland, and did not change significantly over the course of the experiment. We use the micronet data (http://grl.ars.usda.gov/micronet/) of ground and air temperature measurements for validation. The daytime observations from the satellites are for late afternoon hours, giving us an opportunity to examine the effect of large solar zenith angles on the temperature estimates. We also study the spatial variability of the temperature estimates and discuss their implications for hydrologic data assimilation.

In section 2 we describe the details of the data used in the study. In section 3 we review the estimation algorithm for the surface temperature estimation from the AVHRR data. The results of the analysis are described in section 4 and conclusions are given in section 5.

2. Data Description

2.1. AVHRR Data

The AVHRR instruments aboard the NOAA satellites were designed for meteorological observations but provide data that have subsequently been successfully used in a variety of applications [Campbell, 1996]. AVHRR is a scanning radiometer, making calibrated measurements of upwelling radiation from pixels scanned across the satellite track. The instrument collects data at roughly 1100 m resolution in five channels (two visible and three infrared) from an altitude of 833 km. The satellites have a 102 min period and a swath width of 2400 km, allowing for data collection for the entire globe twice daily. Data obtained directly from the satellite scans is called high-resolution picture transmission (HRPT). Alternatively, an onboard computer aggregates data from one visible and one infrared channel of the 1 km data to 4 km resolution, providing broader geographic coverage in the same volume of data. This is called automatic picture transmission (APT). One full orbit of APT data is called global area coverage (GAC) data, while 10 min of full resolution HRPT data is called local area coverage (LAC) data, covering approximately a 2320 pixel by 780 pixel area where each pixel is 1.1 by 1.1 km.

The data used in this study were collected by the AVHRR instruments aboard the NOAA-12 and NOAA-14 satellites, the only AVHRR satellites operational during the SGP97 study. The spectral characteristics of the sensors in different channels is given in Table 1. LAC data for 34 dates during June, July, and August 1997 were obtained for the SGP97 site from the Satellite Active Archive operated by NOAA. The images were then calibrated, converting radiances in the visible bands (channels 1 and 2) to spectral albedo values and radiances in the thermal bands (channels 3, 4, and 5) to blackbody temperatures [Di and Rundquist, 1994]. This calibration did not include the nonlinear corrections in the thermal bands recommended by NOAA; however, the errors introduced by neglecting these corrections are relatively small, less than 0.2 K for NOAA 14 and similar for NOAA 12. Earth location data supplied within the raw AVHRR data allow for mapping onto a latitude-longitude grid. The images, converted to a UTM zone-14 projection, were subsequently clipped to a 64 x 64 pixel size (to facilitate statistical analysis of the images), corresponding to a 70.4 x 70.4 km\(^2\) area surrounding the Little Washita watershed.

2.2. Micronet Data

Air and soil temperature measurements were obtained from 42 Agricultural Research Service (ARS) micronet stations in the Little Washita River watershed. The locations of these micronet sites are listed in Table 2. Plate 1 shows the locations of the micronet sites within a digital elevation model (DEM) grid with approximately the same limits as the 64 x 64 satellite images. The soil temperature data from site 147 was determined to be unreliable, often reporting temperatures 20\(^\circ\) above average. Therefore all data from this site were discarded in our study.

Air temperature was measured at a height of 1.5 m using a sensor housed in a standard pie-plate shield. Ground temperature was measured by thermistor probes physically embedded in the ground at \(~5\) cm depths. Air temperature measurements were made every 5 min, while ground temperature measurements were made every 15 min. Although air temperature measurements occurred with greater frequency, for the sake of

### Table 1. AVHRR Spectral Channels for NOAA-12 and NOAA-14 Satellites

<table>
<thead>
<tr>
<th>AVHRR Spectral Channels (μm)</th>
<th>NOAA 12</th>
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<tr>
<td>1</td>
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<td>3.55–3.93</td>
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<tr>
<td>4</td>
<td>10.50–11.50</td>
<td>10.30–11.30</td>
</tr>
<tr>
<td>5</td>
<td>11.50–12.50</td>
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### Table 2. Coordinates of the Little Washita Micronet Sites

<table>
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<tr>
<th>Site ID</th>
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<th>Longitude (UTM)</th>
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</table>

See Plate 1.
Plate 1. Locations of micronet stations superimposed on digital elevation data. The elevations are in meters above sea level.
consistency we used only data from time steps for which ground temperature was also available.

3. Review of Estimation Algorithms

3.1. Estimation of Surface Temperature

The most widely accepted and validated method for surface temperature estimation is the split-window technique, so called because it uses data from two or more satellite channels in atmospheric windows. Thermal radiances as observed by the satellite can be converted, through inversion of the Planck function, to blackbody temperatures. By assuming that for two channels relatively close together, the atmospheric contribution to the measured radiances is the same and that transmittance differences in the two channels are due solely to differences in the absorption of atmospheric water vapor, the use of two channels allows for estimation of the temperature of the surface observed by the satellite. The resulting equation is [Price, 1984]

\[ T_S = T_{b1} + \frac{1}{b_2} (T_{b1} - T_{b2}), \]  (1)

where \( T_S \) is the temperature of the surface as seen by the satellite, \( T_{b1} \) and \( T_{b2} \) are the respective blackbody temperatures sensed in the two channels, and \( b_1 \) and \( b_2 \) are the water vapor absorption coefficients in the two thermal channels, respectively.

AVHRR channels 4 and 5 are particularly suited to this analysis. However, since the ratio \( R = b_2/b_1 \) is a somewhat abstract parameter, most studies using the split window technique have used regression methods to determine this value. Both Price [1984] and Vidal [1991] found that \( R = 1.33 \) gave results accurate to about 2 K.

A difficulty with the split-window technique for surface temperature derivation is in specifying the emissivity. In the derivation of (1) it was assumed that the emissivity in each band was the same. The split-window method was originally derived for sea surface, which has a relatively uniform unit emissivity, thus this assumption is a good one. However, over the land surface the emissivity in each band may vary slightly, although the value is quite close to 0.96 [Vidal, 1991]. Becker [1987] showed that

\[ T'_5 - T_S = 50 \frac{1 - \bar{e}}{\bar{e}}, \]  (2)

where \( T'_5 \) is the actual surface temperature, \( T_S \) is the surface temperature calculated via the split-window method (equation (1)) and \( \bar{e} \) is the mean emissivity in AVHRR channels 4 and 5.

It has been recommended [Prata, 1993] that pixels with large view angles be excluded from analysis due to uncertainties introduced by longer atmospheric paths. In this analysis, because the study area was in the center of the LAC data, zenith angles were small and therefore no data were excluded.

Using (1) with \( R = 1.33 \), surface temperature images were generated from the calibrated AVHRR images. Surface temperature images were then corrected for surface emissivity by employing the adjustment described by (2) using a mean emissivity of 0.96.

3.2. Identification of Cloud-Contaminated Pixels

Finally, images were processed to determine cloud-contaminated pixels to exclude them from further analysis. Methods for determining contaminated pixels were based upon the TeraScan software algorithms developed by the Space Oceanography Group at the Johns Hopkins University Applied Physics Laboratory [Monaldo, 1996]. The TeraScan procedures are consistent with other recommendations, such as those used to process TOVS soundings [McMillin and Dean, 1982]. The sequence of steps to identify cloudy pixels involves several filters. The criteria are as follows:

3.2.1. Channel 4 difference. The presence of clouds in a pixel will change the apparent brightness temperature. If we assume that the land surface temperature is not extremely variant, it would follow that a large difference in temperature in a local region may indicate the presence of clouds. Therefore if the difference between the maximum and the minimum channel 4 brightness temperatures in a \( 3 \times 3 \) region is above a cutoff value, the center pixel is considered contaminated. The values used for this analysis are 2.5 K for daytime images and 1 K for nighttime images.

3.2.2. Channel 2 difference. A large variation in local channel 2 albedo can be indicative of cloud contamination. If the difference between the maximum and the minimum channel 2 albedo values in a \( 3 \times 3 \) region is greater than 2\%, the center pixel is considered contaminated. This test is only used for nighttime images.

3.2.3. Channels 3 and 4 difference. Because channels 3 and 4 absorb different proportions of water vapor, a large difference (more than 5 K) in the brightness temperatures in these two channels is an indication of cloud contamination. Since channel 3 may contain reflected sunlight, this test is not used for daytime images.

3.2.4. Maximum channel 2 albedo. A large channel 2 albedo is an indicator of cloud contamination. Therefore a pixel with a channel 2 albedo of 8\% for a daytime image or 2\% for a nighttime image is considered contaminated.

3.2.5. Minimum channel 4 temperature. A channel 4 brightness temperature that is very low could indicate that the satellite is seeing cloud-top temperatures. Thus if the temperature in a pixel is less than 283 K, the pixel is considered contaminated.

To be considered clear, a pixel had to fail all five of the above criteria. This analysis eliminated 23 of the original images, as they were deemed significantly cloudy, having a total cloud cover greater than \( \sim 30\% \) over our study area. The dates and timing of the remaining 12 images are given in Table 3.

4. Results and Discussion

4.1. Comparison of Ground and Satellite Data

The spatial distribution of the estimated temperatures for each image are shown in Plates 2 and 3. The pixels identified as cloudy are set to a value of 0 K and appear dark in the figures. The day and nighttime images are grouped separately. Many images show several pixels with relatively cold temperatures (for example, see images for June 11, June 30, and July 9). We believe that these pixels represent partially cloudy areas that are not excluded by the cloud detection algorithm described earlier. Figure 1 shows the timing of all images superimposed on daily precipitation logs obtained from the micronet data. July 4 and August 14 had rainfall during the early morning hours (see Figure 6).

To facilitate comparison of the surface meteorological measurements and satellite estimates, those pixels corresponding to the micronet sites were identified by matching the latitude
and longitude of the micronet sites to individual pixel coordinates within the images. It should be noted at this point, however, that while the surface measurements are point measurements and therefore represent highly localized temperature values, the satellite estimates are averages over 1.1 km × 1.1 km pixels; thus the satellite and surface data have significantly different scales. Furthermore, the surface measurements used in this comparison are at the nearest quarter hour after the time the satellite image was begun. This means that the surface data used can be 5 to 10 min displaced from the time that the satellite data for the study region was obtained, as the study region is in the middle of the LAC data. Inspection of the data records of the ground and air temperatures showed that the maximum error introduced by this discrepancy was ~0.2 K, occurring during the daytime observations. Therefore no interpolation was used. There is virtually no error associated with this approximation for the nighttime data.

Figures 2 and 3 show the box plots of satellite estimates and air and ground temperature measurements for each image. Figure 2 represents daytime images, while Figure 3 represents nighttime images. The box indicates the interquartile range, or the range of values falling between the 25th and 75th percentile of the data. The middle white strip indicates the median. The whiskers are drawn at 1.5× (interquartile range). Values beyond this range are drawn individually. Comparison of temperature range for an entire scene and those corresponding to the micronet sites (compare s1 and s2 in Figures 2 and 3) shows that the subset of pixels corresponding to the micronet sites exhibit the same distribution as that of the entire image (except for the outliers) and will therefore be regarded as representative of the entire scene.

On several days the distribution of the satellite estimates show a large negative skew (June 11, 25, and 30; see also Table 4) due to the problem of partial cloud contamination discussed earlier. Also, the ground temperature measurements during both the daytime and the nighttime show much higher spread in the interquartile range than either the satellite estimates or the air temperature measurements. This is attributed to the issue of scale. The satellite pixels represent averages over 1.21 km², whereas the ground data are a point measurement and are thus highly localized. This would cause the ground measurements to show higher variability. In the case of the air temperature, however, because the air is subjected to some degree to mixing due to winds, air temperature measurements tend to be more representative of large areas than ground temperature measurements. Because of this issue of scale, it is appropriate to compare the mean surface measurement data with the mean satellite data for the same pixels. Table 4 compares the mean satellite data for pixels corresponding to micronet sites with the mean surface measurement data. Figures 4 and 5 show the mean satellite estimates for the entire scene compared with the mean surface data. In general, the satellite estimates are slightly higher than the 5 cm ground temperature measurements for the daytime data, i.e., exhibit a warm bias (1.28 K mean bias) but lower than the ground temperature measurements for the nighttime data, i.e., show a cold bias (~1.25 K mean bias).

The biases are within the 2 to 3 K error range reported in previous studies and may be due to the issue of scale and the fact that the in situ measurements are at a depth of 5 cm. During the daytime the soil temperature is generally lower than the surface temperature, so measurements at the surface would report higher temperatures than at a 5 cm depth. The reverse is true during the night, when the soil temperature is higher than the surface temperature. The satellite estimates calculated in this study are measurements of surface temperature, and thus the observed biases of the surface with respect to the ground at 5 cm are much as would be expected. It is therefore reasonable to assume that the biases found in this study are at least in part related to the above.

No discernible pattern is found for days with rainfall events. Figure 6 shows the time of satellite observation superimposed on rainfall rate over a 24 hour period for two such cases (July 4 and August 14; see also Figure 1). From Table 4 and Figure 2 we see that the satellite underestimates the temperature on July 4 but overestimates on August 14.

Some studies have used an expanded technique to compute air temperature estimates from daytime AVHRR data [Prihodko and Goward, 1997; Czajkowski et al., 1997]. The temperature-vegetation index (TVX) method used in these studies extrapolates air temperature from the relationship between satellite-estimated surface temperature and a spectral vegetation index such as normalized difference vegetation index (NDVI), based upon the idea that air temperature can be estimated from the skin temperature of a full canopy. However, as pointed out by Czajkowski et al. [1997], for large solar zenith angles, such as during the morning and late afternoon hours, shelter height air temperature is the same as the average satellite-estimated surface temperature, evidenced by an NDVI versus temperature slope of close to zero degrees. As indicated in Table 3, all of the daytime images used in this study were taken around 1930 or 0830 LST, consequently solar zenith angles are quite large, of the order of 70° deg. Furthermore, brief analysis of NDVI for the scenes confirmed a generally flat TVX slope. In this case, then, it is reasonable to compare satellite estimates with air temperature measurements for the daytime measurements. Comparison to nighttime measurements is included for the sake of completeness.

The satellite estimates are considerably greater than the air temperature measurements for both daytime and nighttime observations. In fact, we see from Table 4 that the biases and root-mean-square error are greater with respect to air temperature than the ground temperature.

4.2. Spatial Variability

To use the satellite estimates for improving hydrologic model forecasts, we need to get an assessment of its spatial variability, typically measured through the correlation length.

### Table 3. Dates of Cloud-Free Satellite Images Used in the Analysis

<table>
<thead>
<tr>
<th>Date</th>
<th>Julian Day</th>
<th>Local Time</th>
<th>Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/11/97</td>
<td>162</td>
<td>0410</td>
<td>NOAA 14</td>
</tr>
<tr>
<td>06/11/97</td>
<td>162</td>
<td>1930</td>
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The local time represents daylight savings time.
Plate 2. Daytime satellite temperature estimates for entire scene. Dates horizontally from top left: June 11 and 25, 1997; July 4 and 13, 1997; August 5, 9 and 14, 1997. Black areas represent cloud-contaminated regions.
Plate 3. Same as Plate 2 but for nighttime observations. Dates horizontally from top left: June 11 and 30, 1997; July 9, August 5, and August 23, 1997.
A longer correlation length indicates greater homogeneity and vice versa. Table 4 shows that the correlation length for the temperature estimates during the daytime are on an average significantly larger than that of the nighttime with a mean of 8.6 and 5.4 km, respectively. The correlations were computed by considering only the noncloudy pixels. They are nearly isotropic and typically have an exponential decay with respect to the radial lag $\tau = \sqrt{\tau_x^2 + \tau_y^2}$ (Figures 7 and 8); that is, 
$$
\rho(\tau) = e^{-|\tau/b|},
$$
where $b$ is the correlation length, and $\tau_x$ and $\tau_y$ are lags in the $x$ and $y$ directions. The range $\epsilon$, i.e., the distance beyond which any two values may be considered uncorrelated, is given by $\epsilon = 3b$ for the above exponential model [Christakos, 1996]. This suggests that the average range is about 25 and 16 km for the day and nighttime observations, respectively. However, because of the wide spread in the correlation length (see Table 4), the individual values of $\epsilon$ can be quite different.

The variance of a random field, such as the skin temperature, decreases with increase in the averaging interval. This relationship is given as [Vanmarcke, 1988]

$$
\sigma_T^2 = \gamma(T)\sigma^2,
$$
where $\sigma^2$ and $\sigma_T^2$ are the variances of the random field and that obtained after averaging over a window of length $T$, respectively. The variance function $\gamma(T)$ measures the reduction of the point variance $\sigma^2$ under local averaging. For the exponential correlation model (3) it is given as [Vanmarcke, 1988]

$$
\gamma(T) = 2\left(\frac{b}{T} \right)^2 \left(\frac{T}{b} - 1 + e^{-T/b}\right).
$$
Alternatively, writing the averaging length $T$ as a multiple of the correlation length $b$, i.e., $T = ab$, we can obtain

$$
\gamma(T) = 2\left(\frac{1}{a}\right)^2 (a - 1 + e^{-a}).
$$
This result indicates that for $a = 3$, the average process captures only about 45% of the point variance.

The following implications can be drawn from these results for the assimilation of skin temperatures in hydrologic models:

1. By choosing the model grid size of the order of the observed range (~25 km for the SGP site), we can treat the temperature observations for each grid box as essentially spatially uncorrelated.

2. The trade-off, however, is that we capture only about half the true spatial variability. For smaller grid sizes, which will enable us to capture better the point variability, spatial correlation will need to be accounted for.

Both of the results are a consequence of the heterogeneity of the temperature distribution. The shorter the correlation length, the larger the loss of variance information due to averaging with increasing window size, and vice versa.

5. Conclusions

The aim of the study was to (1) explore the differences in the accuracy of satellite-derived land-surface skin temperature for day and nighttime observation; (2) assess the effects of large solar zenith angles; and (3) develop an understanding of the spatial variability of the observed temperatures.

We find that observed biases with respect to the ground temperature, both during day and night, are small. However, except for one rainy day measurement, there consistently was a warm bias during the day and a cold bias during the night.
The lack of any large bias in the satellite estimates is a departure from the results of some other researchers, particularly over the FIFE site [Schmugge and Schmidt, 1998], who report that the split-window technique overestimates the surface temperature by as much as 4° deg. Other authors, however, did not find any systematic bias [Vidal, 1991]. Schmugge and Schmidt [1998] explain that a potential reason for the overestimation found for the FIFE site is that the surface measurement stations in the that study were enclosed and thus were preferentially making measurements over a shaded surface. That was not the case in the SGP97 study, which may explain why the same bias was not found.

Contrary to the hypothesis that at large solar zenith angles the observed temperatures are representative of the shelter height air temperature, we find that the observed temperatures are still closer to the ground temperatures than the air temperature. The results for air temperature comparison have some implications for the usefulness of the TVX technique. NDVI is a strong function of solar angle, and therefore the TVX slope is dependent not only on the surface characteristics but also on the time of day. A correlation between satellite estimates and daytime air temperature measurements is not apparent in this study, because the mean biases were quite large (3.05 K), as shown in Table 4. This is presumably due to the large solar angles for images in this study. Further research therefore may be needed to define a range of solar angles for which the method is applicable.

The correlation is nearly isotropic and has an exponential decay. The correlation lengths demonstrated tremendous spread both during the day and night with the mean during the day being 50% larger than that during the night. The average correlation length of 8.63 km during the day is much smaller

Table 4. Statistics of Satellite-Derived Temperature Estimates in Relation to Ground-Based Surface and Air Temperature Estimates for Several Days in 1997 for the SGP Experimental Site

<table>
<thead>
<tr>
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<td></td>
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</tr>
<tr>
<td>06/11</td>
<td>300.29</td>
<td>1.971</td>
<td>-2.995</td>
<td>11.30</td>
<td>1.62</td>
<td>2.03</td>
<td>1.52</td>
<td>2.48</td>
</tr>
<tr>
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<td>0.827</td>
<td>0.341</td>
<td>6.41</td>
<td>4.31</td>
<td>4.45</td>
<td>1.69</td>
<td>2.73</td>
</tr>
<tr>
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<td>0.802</td>
<td>0.254</td>
<td>8.76</td>
<td>4.54</td>
<td>4.66</td>
<td>-1.37</td>
<td>2.16</td>
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<tr>
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<td>1.159</td>
<td>0.348</td>
<td>20.02</td>
<td>2.47</td>
<td>2.65</td>
<td>2.33</td>
<td>3.11</td>
</tr>
<tr>
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<td>1.557</td>
<td>-4.320</td>
<td>2.22</td>
<td>4.79</td>
<td>5.05</td>
<td>0.84</td>
<td>3.74</td>
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<tr>
<td>08/09</td>
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<td>0.537</td>
<td>2.586</td>
<td>2.21</td>
<td>0.48</td>
<td>0.75</td>
<td>0.92</td>
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</tr>
<tr>
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<td>-2.010</td>
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<tr>
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<td>8.90</td>
<td>3.15</td>
<td>3.28</td>
<td>3.13</td>
<td>3.43</td>
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<tr>
<td><strong>Night</strong></td>
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<td></td>
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<td>3.39</td>
<td>3.64</td>
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<tr>
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<tr>
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<td>2.65</td>
<td>2.87</td>
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<td>3.01</td>
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<tr>
<td>Mean</td>
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<td>1.014</td>
<td>0.130</td>
<td>14.72</td>
<td>2.65</td>
<td>2.87</td>
<td>-2.08</td>
<td>3.01</td>
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</table>

*Note that the mean biases and root mean square (rms) error report the results of the satellite estimates for individual pixels over the micronet sites with respect to the corresponding micronet surface data; gd., ground. Read 06/11 as June 11.

![Figure 4](image4.jpg)  **Figure 4.** Daytime mean surface measurements versus mean satellite-estimated temperatures for entire scene; plus, ground temperature; triangle, air temperature.

![Figure 5](image5.jpg)  **Figure 5.** Same as Figure 4 but for nighttime images.
than the grid sizes typically used in short-time hydrology/mesoscale forecasts. This suggests that for modeling purposes the temperatures in each grid box may be treated as uncorrelated. However, the variance captured can be significantly smaller than the true value.

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References


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