A Window-Based Technique for Combining Landsat Thematic Mapper Thermal Data with Higher-Resolution Multispectral Data over Agricultural Lands

M. Susan Moran
USDA Agricultural Research Service, U.S. Water Conservation Laboratory, Phoenix, AZ 85040

ABSTRACT: Landsat Thematic Mapper (TM) thermal data (TM6), acquired at a spatial resolution of 120 by 120 m, are too coarse to delineate surface temperatures of moderately-sized agricultural fields. A statistical method was developed to combine lower-resolution TM6 data with higher-resolution (30 by 30 m) TM reflective data based on the relation between TM6 and the TM red and near-IR bands. The method utilized a processing "window" to compute statistics for each pixel based on values of neighboring pixels. The window-based method was compared with a look-up table method that had previously been applied to SPOT multispectral and panchromatic data. Both methods were successful in improving the visual appearance of the TM6 image and retaining the original thermal spectral information over diverse agricultural landscapes. The window-based method produced an image with crisper field boundaries but the look-up table method was more successful in preserving narrow features, such as roads and berms.

INTRODUCTION

SURFACE TEMPERATURES (T_s) are a major component of a number of algorithms developed to evaluate agricultural parameters such as crop stress (Idso *et al.*, 1981; Jackson, 1982), evapotranspiration (Price, 1982; Reginato *et al.*, 1985; Jackson *et al.*, 1987), crop yield (Idso *et al.*, 1979), and soil moisture (Reginato *et al.*, 1976). Most algorithms were developed and tested with T_s measurements made at near-ground level or from low-altitude aircraft. As such, the sensor spatial resolution was adequate for agricultural landscapes characterized by small, discrete fields. However, when these algorithms are extended to satellite-based sensors, the relative coarseness of thermal sensors (120 by 120 m for Landsat Thematic Mapper (TM)) makes it difficult to adequately specify surface temperatures of individual fields. Field boundaries and roads, often at a different temperature than the field of interest, can contaminate many pixels.

As an example, consider a resolution of 120 by 120 m relative to a moderately sized rectangular agricultural field, 2.0 by 0.25 km in size (Figure 1A). In the long direction, over fifteen 120-m pixels lie within the field boundaries, relatively unaffected by border temperatures. In the short direction, a maximum of four pixels lie entirely within the field boundaries. When a vegetated field of this size is surrounded by fallow fields, all border pixel values will likely be a composite of the temperatures of the bare soil and the vegetation, and will not be indicative of the condition within the field. Thus, only a small subset of the pixels covering such a field are reliable measurements of the actual surface temperature in the field. In contrast, the TM reflective bands – TM1 to TM5 and TM7 (Table 1) – are acquired at a spatial resolution 16 times smaller than that of the thermal band, that is, 30 by 30 m (Figure 1B).

Several methods have been proposed for combining lower- and higher-resolution bands (Welch and Ehlers, 1987). Such methods have been applied to SPOT HRV 20-m multispectral (XS) data by combination with the 10-m panchromatic (Pan) data (Table 1). Basically, the methods are of two types, those that seek only to obtain optimum image display and those that seek to retain the spectral information in addition to enhancing image display. An example of the former was discussed by Cliche *et al.* (1985) in which techniques were applied to SPOT Pan and XS data to produce visual products resembling color infrared aerial photography. An example of the latter was given by Price (1987).

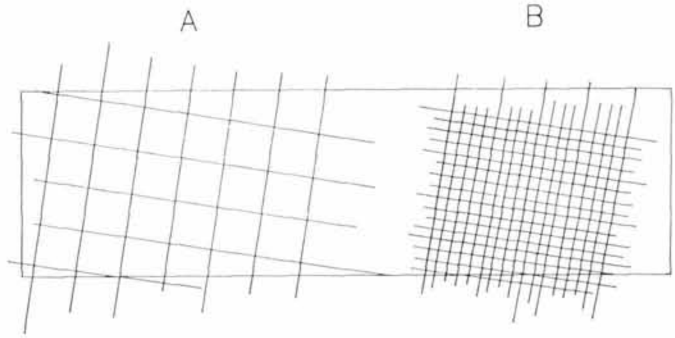

FIG. 1. Illustration of the spatial resolution of Landsat TM thermal (A) and reflective (B) spectral data relative to a 2.0-km by 0.25-km agricultural field.

TABLE 1. SPECTRAL BANDS OF THE LANDSAT-TM AND SPOT-HRV, WHERE λ IS NOMINAL WAVEBAND AND R IS NOMINAL SPATIAL RESOLUTION

	Landsat-TM		SPOT-HRV	
Spectrum Label	λ (μm)	R (m)	λ (μm)	R (m)
panchromatic			Pan 0.51-0.73	10
blue	TM1 0.45-0.52	30		
green	TM2 0.53-0.61	30	XS1 0.50-0.59	20
red	TM3 0.62-0.69	30	XS2 0.61-0.68	20
near-IR	TM4 0.78-0.90	30	XS3 0.79-0.89	20
mid-IR	TM5 1.57-1.78	30		
mid-IR	TM7 2.10-2.35	30		
thermal	TM6 10.42-11.66	120		

Price (1987) presented a method in which the SPOT panchromatic and multispectral data were merged based on statistical analysis. Price found that data from SPOT multispectral channels XS1 and XS2 (Table 1) were highly correlated with the SPOT Pan

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 56, No. 3, March 1990, pp. 337-342.

0099-1112/90/5603-337$02.25/0

channel. Thus, he was able to use the Pan values to estimate values of XS1 and XS2 at 10-m resolution using a linear equation and a simple correction factor. This procedure was shown to be highly successful for XS1 and XS2 but was unsatisfactory for the XS3 data because the Pan and XS3 data were not linearly related. Instead, Price computed a look-up table containing the expected (mean) value for XS3 for each given value in Pan, after the Pan 10-m data were averaged to 20-m resolution. Price derived 10-m data from XS3 using the Pan/XS3 look-up table and applying a correction factor (f) so that the average of the four subpixel values equaled the measured values of the 20-m pixel. Price considered this second procedure to be only moderately successful.

This paper proposes a method to combine the spatial resolution of the Landsat TM reflective bands with the spectral resolution of the thermal band. The method is based on the reported relation between T_s and the normalized difference (NDVI) vegetation index, {(TM4 − TM3)/(TM4 + TM3)}. Gurney *et al.* (1983) found that NDVI accounted for 38 percent of the variance in T_s over a vegetated landscape in central Alaska. Hope (1986) reported that a linear relation existed between NDVI and T_s for a given crop but that this relation varied with different canopies, canopy architectures and soil moisture conditions. According to Hope's findings, it was evident that computation of a single NDVI/T_s relation would not accurately characterize a diverse agricultural land; instead, the NDVI/T_s relation would need to be calculated for each field. The proposed technique accomplishes this by allowing each pixel in the image to be analyzed based on the values of neighboring pixels within a small, surrounding window. The pertinent statistics are calculated as the window moves across the image. Thus, the relation between NDVI and TM6 is determined for each field within the image, regardless of differences in canopy architecture and soil conditions.

WINDOW-BASED METHOD

The window-based band combination method was conceived for application to agricultural landscapes where conditions within fields were assumed to meet two criteria:

- the variation of NDVI was relatively small; and
- values of TM6 lying on or near field boundaries varied more than values in the field center.

These assumptions provide the statistical foundation for the window-based method. The first assumption allows values of NDVI to be used to identify the location of discrete fields within an image. The second assumption implies that the statistical mode of TM6 values within the identified field is representative of the actual thermal emittance from that field. As such, TM6 values deviating from the within-field mode are considered to be contaminated by border effects and are replaced with the mode. In this way, the more variable border values are replaced with values from the center of the field and resolution more closely resembles the 30-m cell size.

The combination process is achieved by using a processing window, starting in the upper left corner of the image and moving across the entire image until all pixels are processed. (In this paragraph, a "pixel" refers to the spectral value representative of a 30-m resolution cell). A 25- by 25-pixel window is delimited around each NDVI pixel, designated as the "center" pixel. Partial windows are delimited for center pixels located less than 12 pixels from the edge of the image. Within the window, all pixels that match the NDVI of the center pixel (within ± 0.05 NDVI) are identified. Thus, the pixels within a uniform area surrounding the center pixel (generally, a single field) are located and cataloged by (x,y) coordinates. Values of thermal data at these (x,y) locations from the TM6 image are compiled and the statistical mode of those values is computed. Then, as the window moves across the NDVI image, a new thermal image (TM6A) is created by placing the values of the TM6 mode in the (x,y) location of the center pixel.

LANDSAT DIGITAL DATA

Landsat TM digital data are commercially available in two formats, CCT-A data, which have been radiometrically corrected for detector differences by histogram equalization, and CCT-P data, which are both radiometrically and geometrically corrected. In both formats, the thermal data are resampled to match the 30-m resolution of the reflective bands. The CCT-A data are available on special request from the EOSAT Corp. and are not geometrically corrected. In the CCT-P geometric correction, a cubic convolution procedure is applied to the thermal data in an attempt to smooth the blocky aspect of the resampled image. Hence, the original spectral response from each 120-m pixel is irretrievably lost. Thus, CCT-A data are more suitable for use in algorithms where the absolute values of surface temperature are necessary.

There are, however, disadvantages to the use of CCT-A data. The TM sensor is composed of 16 detectors for each visible, near-IR, and mid-IR band and four detectors for the thermal band, with the detectors arranged linearly in the along-track direction. As the sensor scans along the forward and reverse direction in the across-track path, every 16-line swath (or 4-line swath for the thermal band) is laterally offset from the previous swath. This offset is accounted for in the CCT-P processing, but not in the CCT-A. Over small areas, i.e., 6 to 10 km, it can be corrected by manually shifting each swath to the left or right until all the pixels are in order. This misalignment is nominally the same for all TM bands, including the resampled TM6 band, so once one band has been corrected, the others can be aligned using the same offsets. The resampling of the TM6 thermal data from 120-m to 30-m resolution results in an additional geometric offset that must be accounted for. Because the sensor scans in the forward and reverse directions, the resampling procedure applied to the thermal data expands each 120-m pixel from left to right in the forward scan and from right to left in the reverse scan. This results in a three-pixel lateral offset in each 16-line swath. So, in addition to the correction applied to all the bands to correct for scan misalignment, the 16 lines corresponding to reverse scans in TM thermal data must be shifted an additional three pixels laterally to compensate for the spatial resampling procedure.

IMAGE PROCESSING

The window-based technique was applied to 15- by 12-km subsets of two Landsat-5 TM CCT-A scenes, one acquired on 23 July 1985 and the other on 24 June 1986, covering an agricultural area in Central Arizona (TM Path 37, Row 37). Each subset included the Maricopa Agricultural Center (MAC), a 770-ha farm located about 48 km south of Phoenix. The farm, which is owned and operated by the University of Arizona, is divided into a research and a demonstration area. The 608-ha demonstration farm has fields up to 0.27 by 1.6 km in size, dedicated to demonstrating new farming techniques on a production scale. On the July date, there was a variety of crops grown on the farm, including cotton, corn, alfalfa, and grapes, and areas of bare soil. On the June date, there were two cotton fields of particular interest. These fields were in the process of being flood irrigated, where one half of each field was wet and the other half dry.

The preprocessing steps for both dates were identical. First, all the bands were corrected for the misalignment due to sensor scanning and TM6 was corrected for the geometric offset due to the resampling procedure, as described in the previous section. Then, an NDVI image was created from the preprocessed TM3 and TM4 images, and then a TM6A image was created based on values in the NDVI and TM6 images.

For comparison purposes, the look-up table technique described by Price (1987) was applied to the TM6 image. Based on all the pixels in the image, a TM6 mean was calculated for each NDVI value and a new thermal image (TM6B) was created at 30-m resolution based on the look-up table values, the original NDVI image, and the correction factor (f) for subpixel mean. The Price look-up table technique, rather than the Price linear equation technique, was chosen because it was reported to be appropriate for circumstances where the coarse and fine resolution data were not well correlated. As discussed previously, Gurney *et al.* (1983) and Hope (1986) reported that the correlation of NDVI and T_s was weak over diverse terrain.

The accuracy of the procedures was tested by comparing the processed TM6 images with T_s data collected using an airborne infrared thermometer (IRT) along transects through the center of 12 large fields in the MAC demonstration farm. The aircraft was flown at a nominal altitude of 150 m above ground level (AGL), resulting in an IRT instantaneous field of view (IFOV) of approximately 40 m diameter. The IRT was mounted normal to the ground surface and data were collected on a small computer at one-second intervals along each field and across field boundaries. During the 15-minute overflight, 190 measurements were collected on 23 July 1985 and 205 measurements on 24 June 1986. A video camera, mounted with the IRT, was used to document surface conditions simultaneous with IRT data collection, and an audible tone was automatically recorded at the moment of each IRT measurement. Based on the video data, each IRT measurement of T_s was located on the NDVI image, and a data set was compiled of T_s values and the corresponding pixel values from the NDVI, TM6, TM6A, and TM6B images.

RESULTS

The results of the window-based and look-up table procedures on 23 July 1985 data are presented in Figure 2. Note the

FIG. 2. The original TM6 image, 23 July 1985 (upper left), the NDVI image (upper right), the window-based enhancement TM6A (lower left), and the look-up table enhancement TM6B (lower right).

TABLE 2. REGRESSION ANALYSIS OF IRT MEASUREMENTS (T_s) WITH CORRESPONDING PIXEL VALUES FROM THE NDVI, TM6, TM6A, AND TM6B IMAGES

23 July 85 ($n = 190$)				24 June 86 ($n = 205$)			
Image	Slope	Intercept	R^2	Image	Slope	Intercept	R^2
NDVI	−7.76	451.3	0.82	NDVI	−5.61	335.4	0.68
TM6	1.85	94.7	0.87	TM6	1.64	106.8	0.83
TM6A	2.01	87.5	0.94	TM6A	1.84	99.8	0.94
TM6B	1.93	91.2	0.91	TM6B	1.77	102.4	0.90

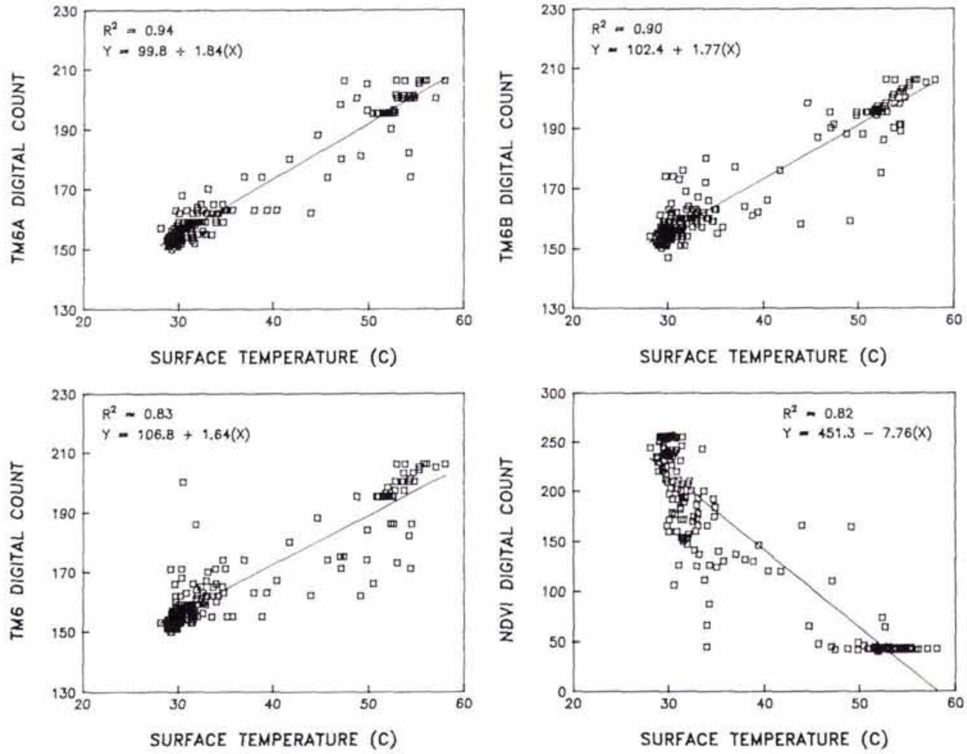

FIG. 3. *Regression analysis of* IRT *measurements* (T_s) *with corresponding pixel values from the* NDVI, TM6, TM6A, *and* TM6B *images acquired 23 July 1985.*

enhanced field delineation in the TM6A and TM6B images compared to TM6. There was some residual blockiness in the TM6B image due to the subpixel mean correction factor (f). Along the borders of dissimilar fields, the f correction tended to raise the low temperature values and lower the high temperature values within a 4 by 4-pixel area and thus retained the blocky character of the original image.

The look-up table method (TM6B) was more successful than the window-based method (TM6A) in preserving narrow features such as roads and field berms. This was due to the nature of the window-based method in which the statistical mode was computed within a limited window surrounding the center pixel. Thus, there were occasions when the mode of the thermal data associated with the NDVI of a narrow feature was actually a composite of the temperatures of the feature and the surrounding area. That is, the thermal pixels straddled the narrow feature and all thermal data associated with the NDVI were contaminated by bordering temperatures. On the other hand, with the look-up table method, the average thermal value associated with each NDVI value was based on all the pixels within the scene subset, and there was less likelihood for this condition to be encountered.

Results of the regression of T_s with the corresponding pixel values from the NDVI, TM6, TM6A, and TM6B images are presented in Table 2. It is notable that the correlation of T_s with NDVI on both dates was unexpectedly high ($R^2 = 0.82$ and 0.68). This could be due to the uniform nature of the agricultural fields in the June and July images, unlike the varied surfaces examined by Gurney *et al.* (1983) and Hope (1986).

Data presented in Table 2 showed that the correlation between T_s and the TM6 thermal data was improved on both dates with application of the window-based or look-up table techniques. The correlation coefficients (R^2) of the regression equations of T_s and TM6 data were 0.87 and 0.83. With the look-up table method, R^2 values increased to 0.90 and 0.91 and with the window-based method the R^2 values were slightly higher, 0.94 on both dates. The regression lines and data for 23 July 1985 and 24 June 1986 are presented in Figures 3 and 4. These figures illustrate the scatter of the TM6 and NDVI data and the good correlation of the TM6A and TM6B data.

The partially irrigated cotton fields in the 24 June 1986 image presented the opportunity for a good test of the window-based method. The cotton fields had approximately the same percent vegetation cover over the length of the field; however, one end had dry soil and the other wet. Under such conditions, one would expect the NDVI to be relatively unaffected by the soil

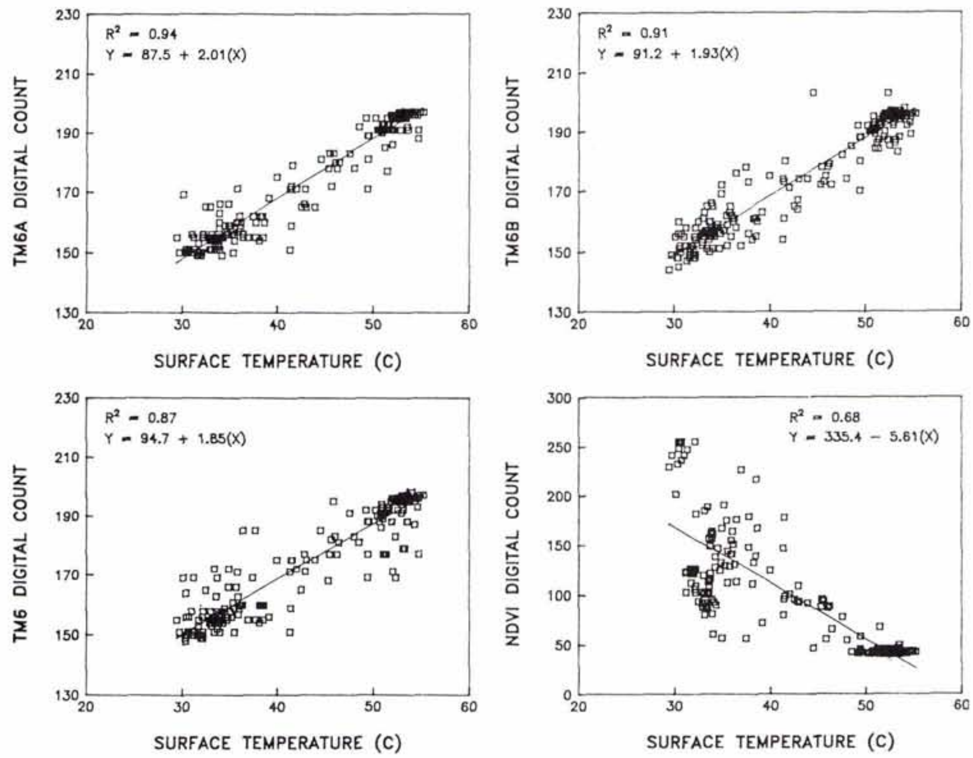

FIG. 4. Regression analysis of IRT measurements (T_s) with corresponding pixel values from the NDVI, TM6, TM6A, and TM6B images acquired 24 June 1986.

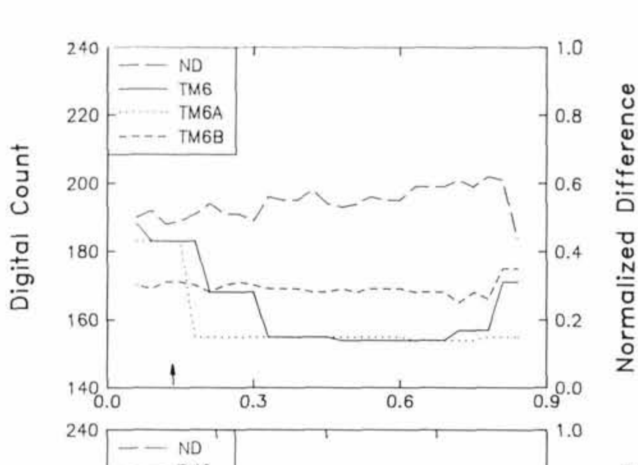

FIG. 5. Values of NDVI, TM6, TM6A (window-based method), and TM6B (look-up table method) along transects through irrigated cotton fields. To the left of the arrow, the soil was dry; to the right, the soil was wet.

moisture difference, whereas TM6 values would be low over the irrigated portion and high over the dry portion. Digital counts along transects running the length of the irrigated fields were compiled from the NDVI, TM6, TM6A, and TM6B images (Figure 5). At the point of irrigation (indicated by an arrow along the X axis), the TM6 values decreased as expected, the NDVI values remained relatively high, and the TM6A values decreased. The TM6B values became more variable over the wet soil but did not decrease significantly from the values over dry soil.

DISCUSSION

The window-based method for combining lower-resolution Landsat TM thermal data with the higher-resolution reflective bands has several advantages. First, the method retains the magnitude of the original digital counts within each field in contrast to enhancement methods that smooth or average the counts. Second, the method accounts for local differences in the relation between the lower- and higher-resolution images. This is advantageous in the case of thermal data, where the overall relation with NDVI is good but there are local variations with crop type, soil color, and moisture. Accounting for such variations improves the overall precision of the procedure.

The accuracy of the window-based method depends upon the nature of the scene. It will be most useful when applied to agricultural areas, fenced rangelands, or regions otherwise characterized by discrete, relatively uniform fields within a diverse landscape. The size of the window is variable and must be gauged by the size of the lower-resolution pixel and the size of the ground fields. The window should be at least five times as large as the lower-resolution pixel. This figure is based on the worst case, where the window straddles two disparate fields and two of the lower-resolution pixels are contaminated by boundary reflectance. In such a case, a 5 by 5-pixel window assures that at least one lower-resolution pixel lies fully within the field of interest. If the fields are very large, the size of the window should be larger to increase statistical accuracy in the calculation of the mode by increasing the sample size.

CONCLUDING REMARKS

The window-based and look-up table methods produced comparable results when applied to Landsat TM thermal data. The window-based method appeared to be slightly more accurate for agricultural scenes, probably due to the computation of the NDVI/TM6 relation within localized windows rather than for the whole image. This additional accuracy was obtained at the expense of processing speed because the window-based method was more computation intensive than the look-up table procedure. Both methods increased the clarity of the thermal image, though the look-up table method tended to retain some of the blocky character of the original TM6 image. This aspect may be of some importance when the image is to be used in visual interpretation or map production. The look-up table method, however, was more successful in preserving narrow objects such as roads and field berms.

REFERENCES

Cliche, F., F. Bonn, and P. Teillet, 1985. Integration of the SPOT panchromatic channel into its multispectral mode for image sharpness enhancements. *Photogrammetric Engineering and Remote Sensing:* 51:311–316.

Gurney, R. J., J. P. Ormsby, and D. K. Hall, 1983. A comparison of remotely sensed surface temperature and biomass estimates for aiding evapotranspiration determination in central Alaska. *Proc. 4th Int. Cong. Permafrost,* pp. 401–404.

Hope, A. S., 1986. *Parameterization of Surface Moisture Availability for Evaportranspiration Using Combined Remotely Sensed Spectral Reflectance and Thermal Observations.* PhD dissert., Univ. of Maryland, College Park, MD 20742, 220 p.

Idso, S. B., R. D. Jackson, P. J. Pinter, R. J. Reginato, and J. L. Hatfield, 1981. Normalizing the stress-degree-day concept for environmental variability. *Ag. Meteorol.* 24:45–55.

Idso, S. B., K. L. Clawson, and M. G. Anderson, 1986. Foliage temperature: Effects of environmental factors with implication for plant water stress assessment and the CO_2/climate connection. *Water Resour. Res.* 22:1702–1716.

Idso, S. B., J. L. Hatfield, R. D. Jackson, and R. J. Reginato, 1979. Grain yield prediction: Extending the stress degree day approach to accommodate climatic variability. *Rem. Sens. Environ.* 8:267–272.

Jackson, R. D., 1982. Canopy temperature and crop water stress. *Advances in Irrigation* (D. I. Hillel, Ed.), Academic Press, pp. 43–85.

Price, J. C., 1982. Estimation of regional scale evapotranspiration through analysis of satellite thermal-infrared data. *IEEE Trans. Geosci. Remote Sens.* GE-20:286–292.

———, 1987. Combining panchromatic and multispectral imagery from dual resolution satellite instruments. *Rem. Sens. Environ.* 21:119–128.

Reginato, R. J., S. B. Idso, J. F. Vedder, R. D. Jackson, M. B. Blanchard, and R. Goettelman, 1976. Soil water content and evaporation determined by thermal parameters obtained from ground-based and remote measurements. *J. Geophys. Res.* 81:1617–1620.

Reginato, R. J., R. D. Jackson, and P. J. Pinter, Jr., 1985. Evapotranspiration calculated from remote multispectral and ground station meteorological data. *Rem. Sens. Environ.* 18:75–89.

Welch, R., and M. Ehlers, 1987. Merging multiresolution SPOT HRV and Landsat TM data. *Photogrammetric Engineering and Remote Sensing* 53:301–303.