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Length-scale analysis of surface albedo, temperature, and normalized difference vegetation index in desert grassland

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Abstract. The Jornada Experiment on the Jornada Experimental Range in southern New Mexico aims at the description of the surface energy balance of a desert grassland ecosystem. A large volume of both field and remote sensing data has been collected from 1995 to 1998. Airborne Daedalus scanner data with a spatial resolution of 4 m have been used to infer the following land surface characteristics: surface temperature, albedo, and normalized difference vegetation index (NDVI). These land surface characteristics can be used as input for land surface models. However, land surface models work with very coarse grid cells of at least 50 × 50 km, in contrast to high-resolution remote sensing data. Also, land surface models are generally based on nonlinear algorithms. Both restrictions lead to scale problems. One apparent question is how to scale up input remote sensing data to the much coarser resolution of the land surface model. The first step is to derive the length scale of the input land surface characteristics. The length scales of the land surface characteristics have been determined with the following two techniques: autocorrelation and wavelet analysis. Within the Jornada Experimental Range, three different sites with different vegetation characteristics were distinguished: grass, shrub, and a transition site with patches of both grass and shrub. The autocorrelation and wavelet analysis showed similar results for the shrub site. For the grass and transition site the wavelet analysis underestimated the length scale of the surface albedo and temperature. The length scale of the surface albedo was 35, 33, and 10 m for grass, transition, and shrub sites, respectively. The length scale of the surface temperature was 31, 20, and 8 m for grass, transition, and shrub sites, respectively. The length scale of the NDVI was 12, 6, and 5 m for grass, transition, and shrub sites, respectively. These small length scales could hamper the use of low-resolution remote sensing data for deriving input data for land surface models.

1. Introduction

The Jornada Experiment carried out at the U.S. Department of Agriculture Agricultural Research Service (ARS) Jornada Experimental Range in southern New Mexico aims at the description of the surface energy balance of a desert grassland ecosystem [*Rango et al.*, 1998]. A large volume of both field and remote sensing data has been collected from 1995 to 1998. Collected remote sensing data consist of visible and thermal infrared imagery, video imagery, and laser profiler data. These data are being used to infer land surface characteristics such as surface temperature, albedo, vegetation indices, and roughness. These land surface characteristics can be used as input for land surface models coupled with atmospheric models.

Atmospheric models are three-dimensional models describing the transport of momentum, water, and heat in the atmosphere. Within an atmospheric model the surface of the Earth is divided into coarse grid cells, whereas the atmosphere is divided into several layers with variable height. In the lowest layer the interaction between atmosphere and surface is modeled. This part is usually referred to as the land surface model (LSM). A LSM describes the exchange of heat, water, and momentum between the atmosphere and the land surface, that is, the surface energy balance. The surface energy balance describes the partitioning of net radiation (Q^*) into soil heat flux (G_0), sensible heat flux (H), and latent heat flux (λE). The processes described in the LSM vary over smaller length scales than the large-scale atmospheric circulation patterns.

Still atmospheric models work with very coarse grid cells of at least 50 × 50 km. Remote sensing data typically have a spatial resolution much smaller than 50 × 50 km. In addition to the scale discrepancy, surface energy balance models are generally based on nonlinear algorithms, which amplifies the scale problem. Therefore high-resolution input data derived from one remote sensor will not necessarily give the same results as low-resolution input data derived from another remote sensor when being used in the same land surface model. The problem arises of how to scale up the land surface characteristics to the much coarser resolution of the atmospheric model. The first step to be taken is to derive length scales of the land surface characteristics involved in the calculation of the surface energy balance therefore determining the maximum resolution required to sample the area. If the resolution

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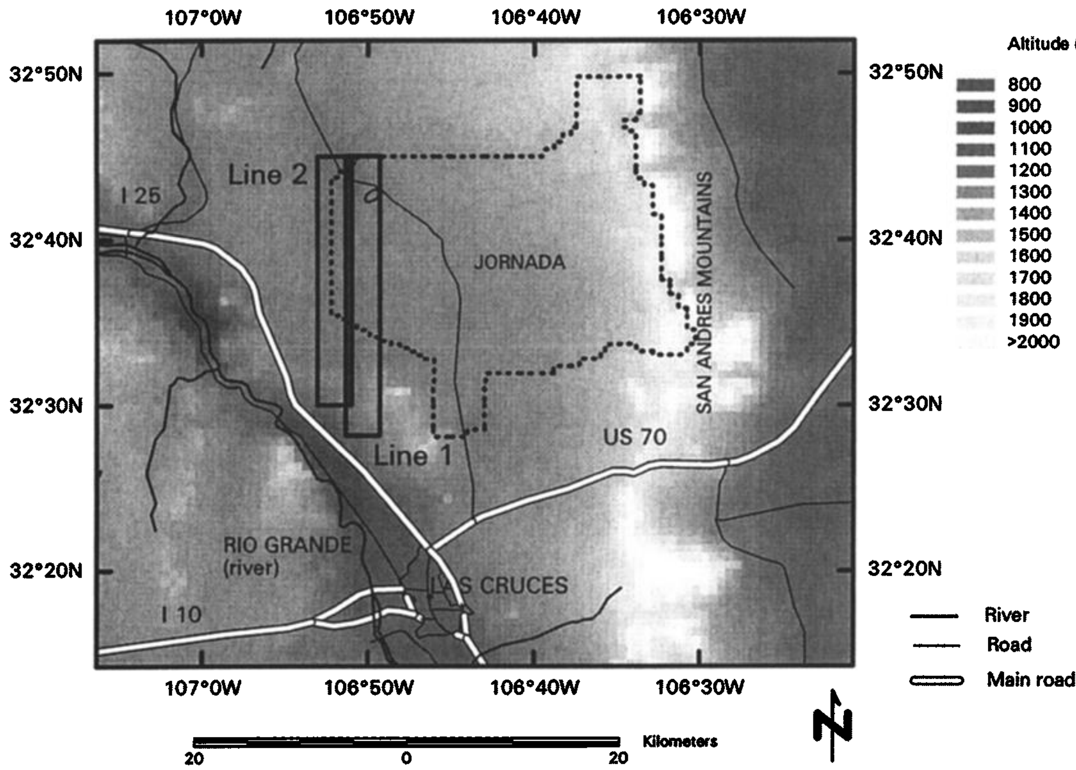

Figure 1. The Jornada Experimental Range site, New Mexico.

is larger than the length scale, the variability present in the landscape will not be fully captured. Errors will be introduced if low-resolution data will be used as input in nonlinear land surface models. High-resolution (~4 m) airborne remote sensing data will be used to derive length scales for surface albedo, surface temperature, and NDVI for three study sites within the Jornada Experimental Range using autocorrelation and wavelet techniques.

2. Study Area

The Jornada Experimental Range, the largest Agricultural Research Service (ARS) field station (783 km^2), is located 37 km north of Las Cruces, New Mexico. Most of the Experimental Range is located on the Jornada del Muerto Plain of the Chihuahuan Desert at about 1200 m elevation. It is situated between the Rio Grande Valley on the west and the San Andres Mountains on the east in the northern part of the Chihuahuan Desert (Figure 1). The crest of the San Andres Mountains is about 2440 m and coincides with the eastern boundary of the Experimental Range.

The climate is characteristic for the northern region of the Chihuahuan desert, the most arid of the North American grasslands. Annual averages for precipitation and temperature are 241 mm and 15°C, respectively. Approximately 55% of the annual precipitation occurs as localized thunderstorms during July, August, and September. Droughts (<75% of average annual precipitation) are common and have occurred in 18 years from 1915 to 1995. The frost-free period averages 200 days, but the effective growing season, especially for perennial grasses, is limited to the summer months. High temperatures, low humidity, and frequent winds during the summer result in large water losses by evaporation. Potential evaporation rates are approximately 10 times the average precipitation.

The vegetation of the Jornada del Muerto plain is characteristic of a subtropical ecosystem in the hot desert biome. Grass communities dominated by black grama (*Bouteloua eriopoda*) have been susceptible to disturbances (such as prolonged drought and overgrazing), and encroachment by shrubs during the last century has been common. Large areas of former grassland, including the northern portion of the study area, are now dominated by honey mesquite (*Prosopis glandulosa*). This conversion resulted in the formation of coppice dunes on the deep, coarse-textured soils, increasing spatial heterogeneity of critically limited nutrients (especially north) required for plant growth [*Schlesinger et al.*, 1990] as well as increasing wind erosion [*Gibbens et al.*, 1993]. The study area encompasses an ecotone between remnant black grama grassland and honey mesquite coppice duneland that has developed in the past 80 years. Without subsequent intervention, further desertification of this grassland is anticipated during the next century.

Within the ecotone, three sites were chosen for intensive studies. The sites were selected to represent a grass, shrub, and grass-shrub transition area. Black grama dominates the grass site and is within a long-term study area where grazing has been excluded. The site is relatively level. Honey mesquite on coppice dunes dominates the shrub site. The dunes vary in height from 1 to 4 m with honey mesquite on each of them. The area between the dunes is usually bare soil. The grass-shrub transition site is an area located between the grass and shrub site with vegetation components from both. Some dunes are present but are usually less than 1 m in height.

3. Data Collection

Data have been collected during field campaigns since 1995. Field campaigns are centered on a Landsat satellite overpass and took place in a dormant season (February 1996), in a dry season (May 1995, 1996, 1997, and 1998), and after the wet season (September 1995, 1996, and 1997). In addition to satellite data, ground data and airborne remote sensing data have been collected.

Field measurements of vegetation/soil reflectance and temperature were acquired along linear transects and at preestablished grid points using visible/near-infrared radiometers, thermal infrared radiometers, and spectroradiometers. Ground surveys of vegetation type and height, leaf area index (LAI), and topographic variation were also made, together with energy balance measurements [*Kustas et al.*, 1998].

The Daedalus 1268 scanner (trade names are provided for the benefit of the reader and do not imply an endorsement of or a preference for the listed product by the U.S. Department of Agriculture or the Winand Staring Centre) provided by NASA Ames recorded the airborne remote sensing data. The Daedalus sensor measures radiances in 12 bands ranging from visible to thermal infrared. Seven of those 12 bands are identical to the seven bands of the Landsat-TM satellite. The spatial resolution of the data is 4 m and has been recorded on June 19, 1997, in the middle of the dry season. Two lines were flown at an altitude of 1524 m parallel to each other. Line one is flown northward, and line two is flown southward. For the position of flight lines one and two, see Figure 1.

4. Retrieval of Land Surface Characteristics From Daedalus Data

4.1. Surface Albedo

Broadband surface albedo has been calculated using the first 10 bands (0.35–2.7 μm) of the Daedalus sensor. Raw digital counts have been converted to radiance measured at the sensor for each band. Conversion factors have been supplied by NASA Ames. The radiance measured at the sensor has been corrected for the atmospheric conditions using the Moderate Resolution Atmospheric Radiance and Transmittance Model (MODTRAN) [*Berk et al.*, 1998] which finally resulted in a surface reflectance per band. These reflectances are used to calculate the broadband surface albedo, using weighing coefficients for the different bands. Also, the effect of the viewing angle on the surface albedo was corrected using the bidirectional reflectance model of *Walthall et al.* [1985].

The calculated surface albedo corresponded well with field measurements of surface albedo sampled by a spectroradiometer. The surface albedo for the Jornada ranges from 0.10 to 0.22. In Figure 2 the surface albedo is shown for the grass, shrub, and transition sites. For the grass site the black grama is the dominant vegetation type and has the lowest surface albedo. Within the black grama vegetation also several spots of bare soil are visible, having a higher surface albedo. The shrub site shows a completely different vegetation structure with the individual shrubs clearly separated from each other. Because of the high spatial resolution of the data (4 m) the coppice dunes with the mesquite bush on top can be distinguished from the surrounding bare soil areas. Finally, the transition site shows that the original black grama vegetation in the middle of the image is gradually taken over by the mesquite bush coming in from the east and west.

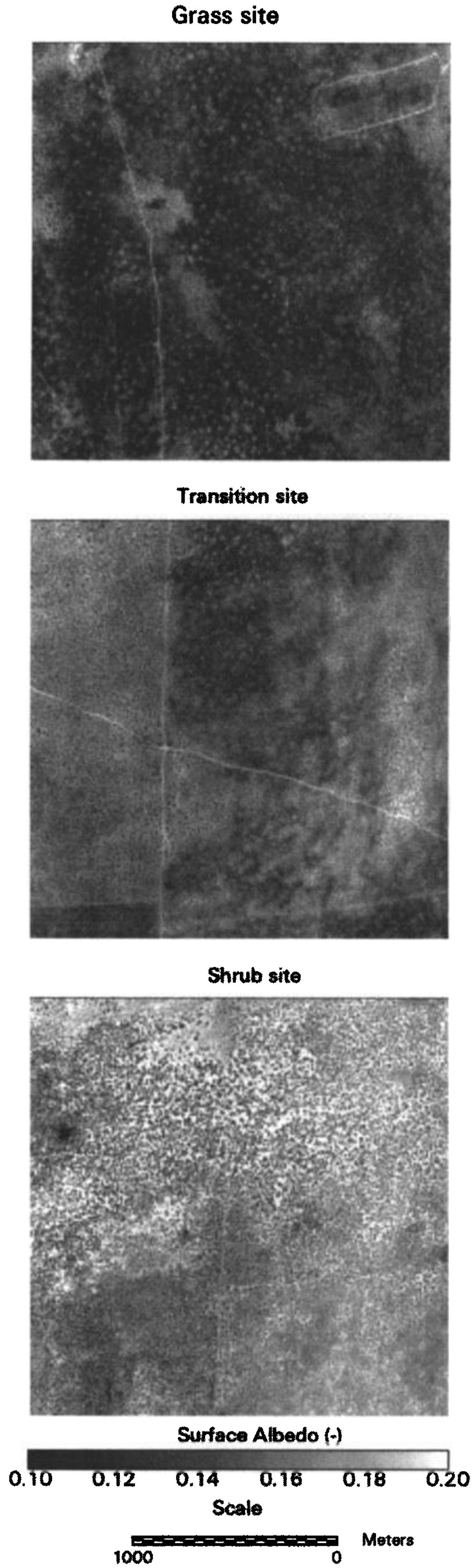

Figure 2. Surface albedo for the grass, transition, and shrub sites based on Daedalus data recorded on June 19, 1997.

4.2. Surface Temperature

The Daedalus surface temperature was corrected using information supplied by NASA Ames. Calibration data were obtained during flight from two blackbody sources, which were viewed during every mirror scan. The first (cool) blackbody is left to float at ambient temperature. The second (warm) blackbody was maintained at a higher temperature than the cool blackbody and was set depending on the desired scene temperature range. For both blackbodies the equivalent Planck radiances were calculated. Using the digital counts for both blackbodies, a linear relationship between Planck radiance and digital count was established. This relationship was used to calculate the Planck radiance for each pixel. Inverting the Planck equation gives the brightness temperature for the whole scene. The range of the temperature for the whole scene is 300–330K (27–57°C).

4.3. Normalized Difference Vegetation Index (NDVI)

Bands 5 and 7 of the Daedalus are identical to Landsat bands 3 and 4. These bands can be used to infer the normalized difference vegetation index (NDVI), defined as the ratio (NIR − R)/(NIR + R), where NIR is the reflectance in the near infrared (band 7) and R is the reflectance in the red part (band 5) of the electromagnetic spectrum. The reflectances for both bands were already derived during the calculation of the surface albedo. The NDVI is an indicator for the amount of green biomass present at the surface. A high NDVI value corresponds with a high amount of green biomass. The NDVI for the Jornada ranges from −0.05 to 0.15 and indicates that there is very little green vegetation present.

5. Tools for Length-Scale Analysis

Two methods were used to infer length scales of land surface characteristics from remote sensing data: autocorrelation analysis and wavelet analysis.

5.1. Autocorrelation Analysis

The autocorrelation function $\rho(r)$ is a measure of the correlation of a spatial variable u with itself and is defined as

$$\rho(r) = \frac{\overline{u'(x)u'(x+r)}}{\sigma_u^2}, \tag{1}$$

where $\rho(r)$ is the autocorrelation at lag r, $u'(x)$ is the deviation of spatial variable u at location x from the spatial mean of u, $u'(x+r)$ is the deviation of spatial variable u from the spatial mean of u at location $x + r$, and σ_u^2 is the unbiased variance. The autocorrelation function, or correlogram, determines the degree of continuity of the data. A good measure for the length scale of land surface characteristics is the integral length scale Lx:

$$Lx = \int_0^\infty \rho(r)\, dr. \tag{2}$$

In this study the integration is terminated at the first zero crossing of the correlogram.

Within image analysis the correlogram has to be calculated for a two-dimensional (2-D) environment. Not only is $\rho(r)$ dependent on the lag, but $\rho(r)$ is also dependent on the direction. The results can be plotted in a correlogram surface, where for each lag and direction $\rho(r)$ is given. Compared to a one-dimensional correlogram, the number of observation pairs increases dramatically and makes computation of the correlogram surface extremely computer intensive. In order to speed up the process, a procedure based on fast Fourier transform was used to calculate the 2-D correlogram.

5.2. Wavelet Analysis

Wavelet analysis is a relatively new tool in geophysics [*Kumar and Foufola-Georgiou*, 1997; *Katul and Parlange*, 1995]. In this study a discrete wavelet transform (DWT) will be used to decompose the data set into an equally large set of wavelet coefficients. Each wavelet coefficient corresponds with a wavelet ψ of scale level j and position k. The decomposition of a data set into wavelet and scaling function coefficients is called a multiresolution analysis [*Mallat*, 1989]. For the analysis of remote sensing data the multiresolution should be performed for a 2-D environment. As a consequence, the DWT will work in three different directions: vertical, horizontal, and diagonal.

In this study the Haar wavelet [*Haar*, 1910] has been chosen. The Haar wavelet is an example of an orthonormal wavelet, so the amount of information is conserved within the multiresolution analysis. The Haar wavelet was chosen in preference to other wavelets because of its suitability for capturing rapid changes in the data [*Mahrt*, 1991]. Another advantage is that within the multiresolution analysis, one of the products at each scale level j is an aggregation of the original data. With the Haar wavelet the aggregated data set for each scale level j would be same as when one would observe the region with the same type of sensor but at a resolution equal to scale level j. Therefore the Haar wavelet is suitable to quantify the loss of information within the data set while degrading the resolution. However, a drawback is the energy leakage to smaller length scales of the Haar wavelet transform. Overestimation of the information present within smaller length scales is likely to happen.

The wavelet coefficients are a measure of the intensity of the local variations of the signal for the scale under consideration. The value of a coefficient will be large when the size of the wavelet is close to the scale of heterogeneity in the signal. The value of a coefficient will be negligible when the local signal is regular for that particular scale [*Ranchin and Wald*, 1993]. The variance of the wavelet coefficients, the wavelet variance, is thus a natural tool for investigating the spatial scales of variability in remote sensing data [*Percival*, 1995]. The wavelet variance is defined as

$$\sigma_{y,j}^2 = \frac{1}{N} \sum_{k=1}^{n_j} D_{j,k}^2, \tag{3}$$

where $\sigma_{y,j}^2$ is the sample wavelet variance of data set y at scale j and $D_{j,k}$ are the wavelet coefficients at position k and scale j and N is the number of elements in the total data set. The number of data points at scale level j is given by $n_j = N/2^j$. In this study the scale level at which the maximum wavelet variance occurs is said to be the length scale of the land surface characteristic under consideration.

6. Results

The length-scale analysis has been performed on the surface albedo, surface temperature, and NDVI imagery derived from the Daedalus data. For the three sites, the grass, shrub, and transition sites, a subset of 512 × 512 pixels (2048 × 2048 m)

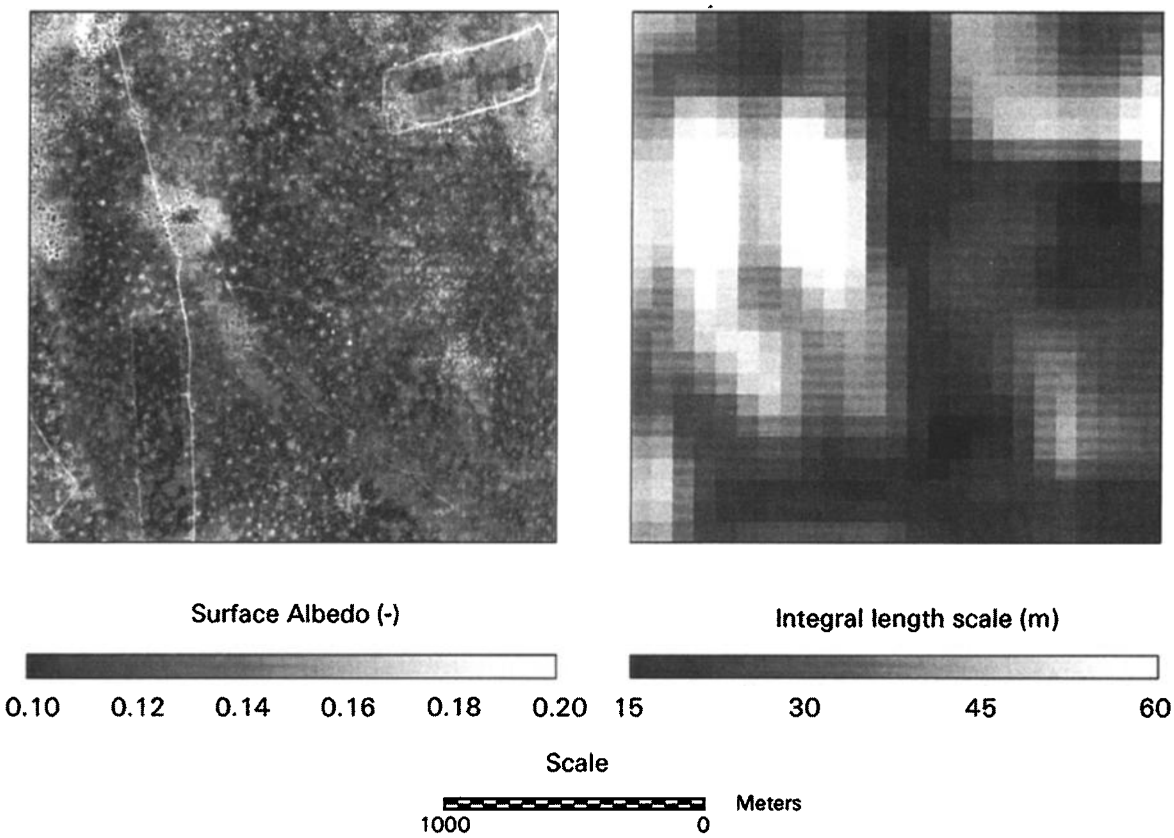

Figure 3. Result of the moving window method for the autocorrelation analysis. (left) Surface albedo of the grass site. (right) Integral length scale for each window at the grass site. Window size is 128 × 128 pixels; step size is 16 pixels.

has been selected from the original data. For both the autocorrelation and wavelet analysis the same type of procedure is used. A moving window of 128 × 128 pixels is shifted over the subset of the three sites for each land surface characteristic. The window is moved each time 16 pixels in the horizontal and vertical direction successively. A smaller step size would lead to a large amount of computing time. As a result, there will be 625 windows for each site and land surface characteristic. For each window a wavelet and autocorrelation analysis is performed. The moving window method is chosen to avoid having large-scale features dominating the length-scale analysis.

6.1. Autocorrelation Analysis

A correlogram surface is computed for each moving window. The correlogram surface shows the correlogram function for each possible direction. From the correlogram surface the omnidirectional correlogram is calculated by taking the average autocorrelation over all possible directions. From this omnidirectional correlogram the integral length scale is calculated. The integration has been terminated at the first zero crossing of the omnidirectional correlogram.

In Figure 3 the results for the surface albedo image of the grass site are shown. The dimension of the image is 512 × 512 pixels, while for the analysis a window of 128 × 128 pixels and a step size of 16 pixels has been used. Figure 3 shows an image with the integral length scale for all moving windows. There is a considerable amount of variability present. The black grama communities in the middle of the image have an integral length scale of about 25 m. The enclosure at the upper right part of the image, which is composed of experimental plots, has a larger integral length scale than the black grama. The surface albedo image shows that in the enclosure larger fields are present. The average field size seems to correspond with the integral length scale; both values are about 50 m. The large patch of bare soil in the middle right part of the image shows the largest integral length scale of about 75 m.

The autocorrelation analysis has been repeated for all three sites for the three land surface characteristics: surface albedo, surface temperature, and NDVI. Figure 4 shows the cumulative frequency distributions of the integral length scale for the three different sites for each land surface characteristic.

For the surface albedo the shrub site clearly has a different integral length scale than the transition and grass site. For the surface albedo of the grass site the smallest integral length scale is about 10 m, and the largest integral length scale is found at 75 m. About 50% of the integral length scales are smaller than 30 m. For the shrub site, there is much less variation. About 50% of the integral length scales are smaller than 10 m. This integral length scale corresponds with the average size of the dunes and the average distance between the dunes. The integral length scale for the surface albedo of the transition site shows that this site has components of both the grass and shrub site. Therefore the integral length scale starts at 10 m similar to the shrub site but also has larger integral length scales, similar to those in the grass site. For the transition site, 50% of the ranges are smaller than 30 m.

The integral length scale for the surface temperature is

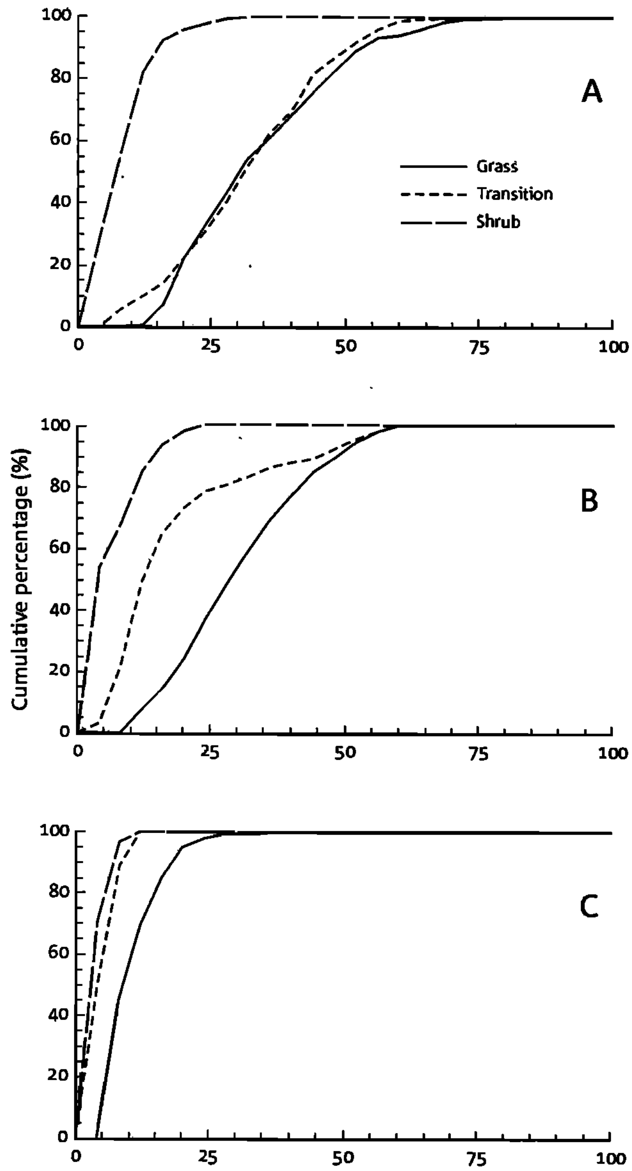

Figure 4. Frequency distribution of the integral length scale for the three different test sites for the following land surface characteristics: (a) surface albedo, (b) surface temperature, and (c) normalized difference vegetation index (NDVI).

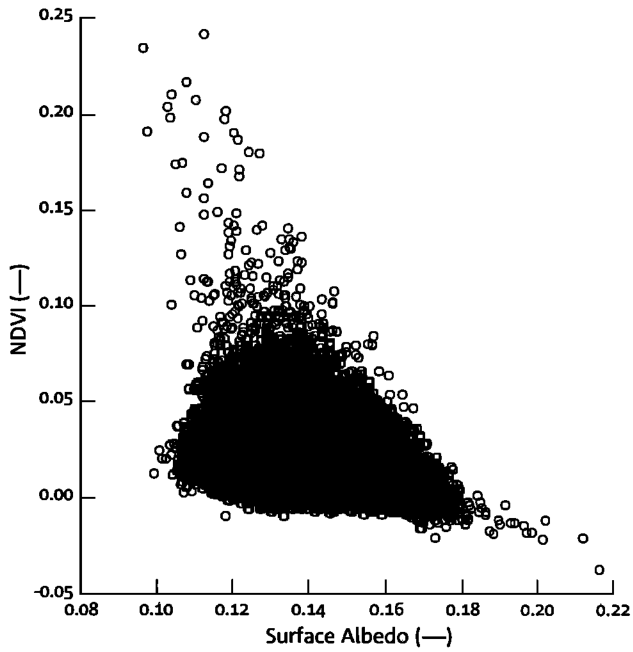

Figure 5. Scatterplot of surface albedo and NDVI for the grass site (25% of the pixels are used, every fourth pixel).

smaller for the transition site than for the surface albedo of that site. This could be an indication that different processes than those that govern the spatial behavior of the surface albedo at that site govern the spatial behavior of the surface temperature. This could have consequences for remote sensing models using both land surface characteristics as input. A possible explanation for the difference in integral length scale could be the influence of shade caused by the mesquite shrubs on top of the dunes. The shade causes temperature differences between the sunlit and the shady site of the dune. Therefore the integral length scale is less than the average size of the dunes. This would explain the small difference in integral length scale for the shrub site and part of the difference for the transition site. The integral length scale of the surface temperature of the grass site is equal to the integral length scale of the surface albedo of that site.

The shrub site shows similar length scales for the surface temperature and NDVI. The mosaic of dunes and bare soil areas together with the shade seem to be the most important characteristics, which govern the spatial patterns of surface temperature and NDVI at this site. However, at the transition and the grass site the integral length scale of the NDVI is much smaller than the integral length scale of the surface albedo. One explanation for this is that there is no linear relationship between the surface albedo and NDVI at these sites. This is illustrated in Figure 5 where a scatterplot of surface albedo and NDVI for the grass site is given. Especially at the lower surface albedo values, the range of NDVI values is quite large. The black grama in the image is represented by the low surface albedo and low NDVI values. A different vegetation type with the same surface albedo value but with higher NDVI values is also present in the landscape, representing a healthier type of vegetation. These two types of vegetation do not exist in separate plant communities but are interspersed. Therefore the NDVI has a larger spatial variability compared with the surface albedo, leading to a smaller integral length scale.

With regard to the integral length scale of the NDVI images the difference between the three sites is not so apparent. For all three sites, there seems to be only small integral length scale. For the grass site, 50% of the dominant integral length scale is less than 10 m, whereas for the shrub and transition site the 50% of the integral length scale is less than 5 m. There is almost no variability in the integral length scales for the NDVI, except for a small part of the grass site.

6.2. Wavelet Analysis

With the wavelet analysis a similar approach as with the autocorrelation analysis has been taken. The moving window method is used with the same window size (128 × 128 pixels) and the same step size (16 pixels). Therefore the wavelet anal-

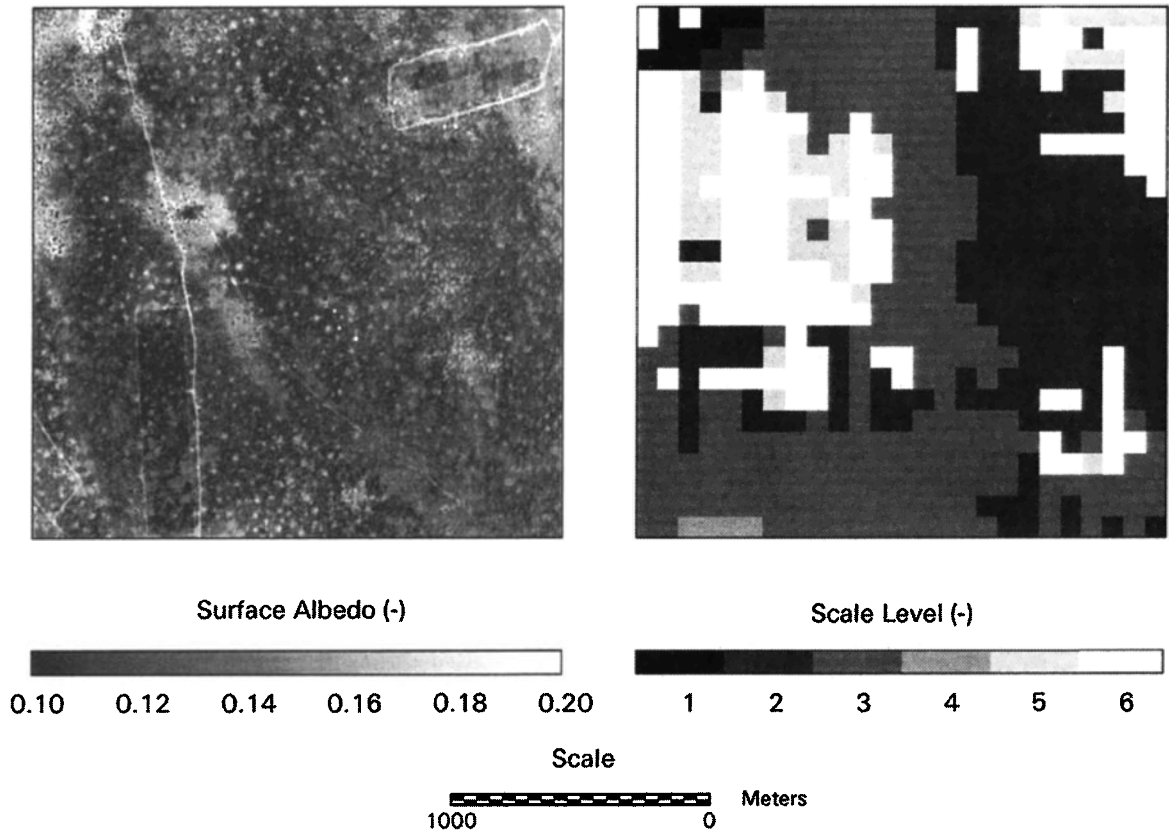

Figure 6. Result of the moving window method for the wavelet analysis. (left) Surface albedo at the grass site. (right) Scale level for which the maximum wavelet variance was found for each window at the grass site. Window size is 128 × 128 pixels; step size is 16 pixels.

ysis has been performed for the same set of windows as the autocorrelation analysis, which makes the results comparable. Here for each window the wavelet variance is calculated by a 2-D multiresolution analysis using the Haar wavelet.

In Figure 6 the results for the surface albedo image of the grass site is shown. For each window the scale level at which the maximum wavelet variance is detected is shown. This scale level is said to be the length scale of the underlying land surface characteristic. Scale level 0 corresponds with 4 m resolution (the original resolution); scale level 1 is twice as coarse: 8 m resolution. With each new scale level the resolution becomes twice as coarse. The grass site shows, in general, that for most windows most of the variability is present at scale levels 2 and 3 (16 and 32 m, respectively). The windows for which this is true have black grama as dominant vegetation type. However, for the enclosure at the upper left part in the image the maximum wavelet variance is found at the highest scale levels 5 and 6 (128 and 256 m, respectively). The same applies for the large bare soil area in the middle right part of the image. Comparison with Figure 3 shows that the length scales obtained by the wavelet and autocorrelation analysis are of the same order of magnitude for the black grama. However, for the other areas the length scales obtained by the wavelet analysis are larger than those obtained by the autocorrelation analysis.

In Figure 7 the average wavelet variance per scale level for all windows is shown for the three sites for each land surface characteristic. The most remarkable feature is that most of the variability present for the three land surface characteristics is limited to the smallest scale of 8 m. Only for the surface albedo of the grass site, is the maximum wavelet variance present at the scale of 32 m. Comparing the three sites, the shrub site contains much more spatial variability than the grass site for all three land surface characteristics. The reason for this is that the shrub site is composed of bare soil and mesquite bush, two features which have large differences in surface albedo, temperature, and NDVI. The grass site is covered mostly by black grama, with some areas of bare soil. The differences in surface temperature, surface albedo, and NDVI are not as large between black grama and bare soil as between mesquite and bare soil. The transition site is a transition zone between the grass and shrub site, showing that the transition site is composed of both black grama and mesquite bush together with bare soil. The overall variability of the transition zone is therefore larger than the grass site but is smaller than the shrub site. The decrease in wavelet variance for the shrub site for all surface characteristics indicates that the dominant length scales for the land surface characteristics are the smallest scale: 8 m. This corresponds with the result obtained with the autocorrelation analysis for the shrub site. In Figure 4 the cumulative distribution function shows a sharp increase after the smallest integral length scale for the shrub site, indicating that the smallest integral length scale is the dominant length scale. The less sharp decrease in the wavelet variance for both the transition and grass site shows that besides the variability present at the smallest scale, there is also some variability present at the

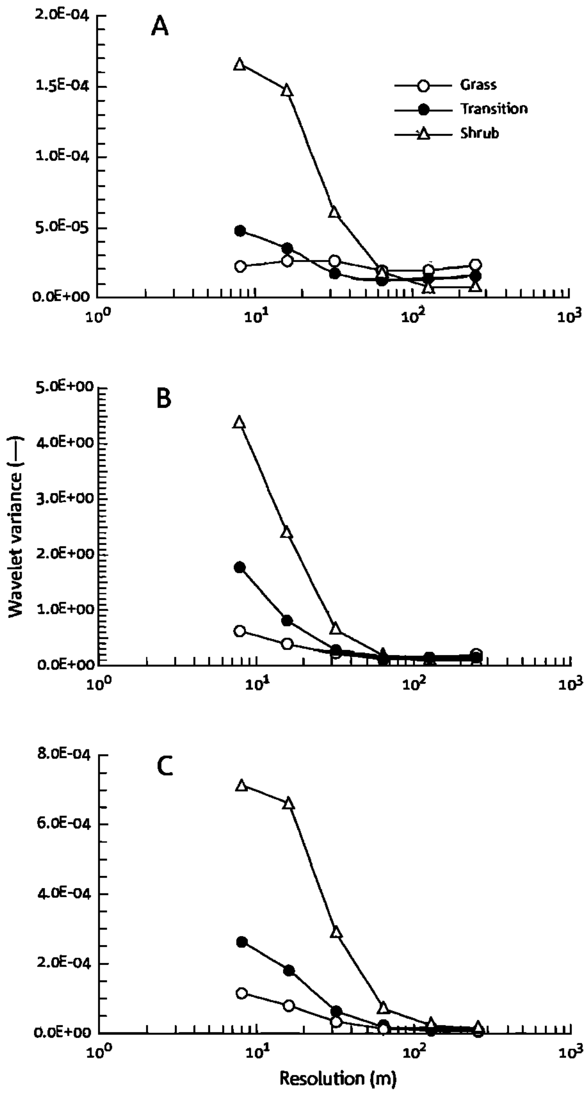

Figure 7. Average wavelet variance for the three different test sites for the following land surface characteristics: (a) surface albedo, (b) surface temperature, and (c) NDVI.

larger scales, most notably concentrated in the length scale of 16 m.

In Table 1 a comparison between the result obtained by the autocorrelation analysis and wavelet analysis is presented. For the autocorrelation analysis the length scale is defined as the integral length scale, whereas for the autocorrelation analysis the scale level at which the maximum wavelet variance occurs is said to be the length scale. A hampering factor in comparing these methods is that the wavelet analysis only uses discrete scale levels (4, 8, 16 m, etc.). The mean values compare well for the NDVI of all sites and the surface albedo and surface temperature of the shrub site. For the remaining land surface characteristics the mean values derived by the wavelet analysis are generally lower than the mean values derived by the autocorrelation analysis, with the exception of the surface albedo of the grass site. For the surface albedo of the grass site, however, the dominant length scale (see Figure 7) is 32 m, which corresponds well with the mean value derived by the autocorrelation analysis, 35 m. The lower values given by the wavelet analysis can be explained by the fact that the Haar wavelet has some energy leakage to smaller length scales. The results of the wavelet analysis are more uniform compared with the results obtained by the autocorrelation analysis. In most cases the length scale equals the smallest scale level (8 m) indicating that most of the variability is present at that particular length scale.

7. Conclusions

Both the autocorrelation and wavelet analysis show that the length scale of surface temperature, surface albedo, and NDVI for the three test sites is small. The length scale is defined as either the integral length scale for the autocorrelation analysis or as the scale level with the maximum wavelet variance for the wavelet analysis. The wavelet and autocorrelation analysis shows that most of the variability is present at length scales smaller than 30 m. This has serious consequences for the type of sensor one uses to infer land surface characteristics. For instance, the Landsat TM data have a spatial resolution of 30 m in the visible region and 120 m in the thermal infrared. This study shows that most of the variability present in the Jornada cannot be captured with Landsat data. The resolution of the thermal infrared sensor of Landsat is much larger than the length scale of the surface temperature at the Jornada site.

The advantage of the autocorrelation analysis is that the length scale can be defined more precisely, while the wavelet transform is bound to discrete intervals. This problem can be solved by using a continuous wavelet transform and will be the subject of another study.

The Daedalus imagery was chosen for studying length scales

Table 1. Statistics for the Length Scale Analysis Using Autocorrelation Analysis and Wavelet Analysis

		Autocorrelation Analysis				Wavelet Analysis			
Site	Land Surface Characteristic	Min	Max	Mean	SD	Min	Max	Mean	SD
Grass	surface albedo	11.11	76.46	35.27	14.32	8.00	256.00	87.07	98.17
	surface temperature	8.96	60.24	31.89	12.52	8.00	8.00	8.00	0.00
	NDVI	4.08	33.39	12.33	5.14	8.00	8.00	8.00	0.00
Transition	surface albedo	4.94	72.51	33.50	14.01	8.00	256.00	17.92	48.64
	surface temperature	3.25	59.60	19.91	14.34	8.00	8.00	8.00	0.00
	NDVI	2.51	11.81	6.47	2.24	8.00	8.00	8.00	0.00
Shrub	surface albedo	2.73	30.83	9.86	5.18	8.00	16.00	9.09	2.85
	surface temperature	2.32	22.87	8.08	5.05	8.00	8.00	8.00	0.00
	NDVI	2.62	11.49	5.29	1.48	8.00	16.00	9.84	3.37

Length scale is defined as the integral length scale for the autocorrelation analysis and the scale level at which the maximum wavelet variance occurs for the variogram analysis. Abbreviations are as follows: Min, minimum; Max, maximum; and SD, standard deviation.

because the sensor resolution would be smaller than the length scales present in the Jornada landscape. The results of the wavelet analysis could indicate that the latter is not necessarily true for the Jornada test sites. For all sites and land surface characteristics, except for the surface albedo image of the grass site, the maximum wavelet variance is found at the smallest scale. A wavelet analysis with imagery with a higher resolution should be performed in order to determine if 8 m is really the actual length scale. One would still expect some variability present at smaller length scales than 8 m. Theoretically, the true spatial variability cannot be quantified unless the spatial resolution of the remote sensing data is less than the size of the individual plants.

Another point of interest is the different length scale found for the three land surface characteristics for the grass and transition sites. This has consequences for using surface temperature, surface albedo, and NDVI derived for the grass site and transition site as input data in a physical model. Combining these data will always introduce an error merely because of the fact that the length scales of these land surface characteristics are not equal. For the shrub site the problem does not exist. The mosaic of dunes and bare soil together with the shade are the most important characteristics which govern the spatial patterns of surface albedo, temperature, and NDVI.

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