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ANALYSIS AND MODELING OF THE RADIATION BUDGET AND NET RADIATION OF A SANDHILLS WETLAND

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Abstract: The surface radiation budget consists of the streams of incoming and outgoing shortwave and longwave radiation flux. Net radiation, the algebraic sum of these four terms, is very significant because it represents the amount of energy available to drive surface climatic, hydrologic, and biological processes. Heterogeneity of the surface is an important factor controlling the spatial variability of the radiation budget. Wetland surfaces such as those in the Nebraska Sandhills are a complex mosaic of cover types and surface conditions and, thus, have potential for great variability in their surface radiation and energy microclimate. In this study, radiation budget data collected using fixed measurement stations and mobile instruments were used to assess the degree and causes of variability in the radiation regime within a typical Sandhills wetland. The site was stratified into four subsystems, high and low marsh, subirrigated meadow, and open water. Results show that there is no significant variability of radiation regime within the marsh, but the marsh, meadow, and water are all separable from each other. Surface albedo appears to be a significant factor separating the subsystems, while the longwave energy balance functions as an "homogenizing" influence. Further analysis indicates that accurate estimates of net radiation can be made using only measurements of solar radiation.

Key Words: radiation budget, net radiation, spatial heterogeneity, Nebraska Sandhills

INTRODUCTION

Solar radiation plays a crucial role in providing the energy necessary to drive climatic, hydrologic, and biological processes at the Earth's surface. In many such applications, however, it is the entire surface radiation budget, rather than merely the solar radiation, that is of interest. The surface radiation budget consists of incoming and outgoing radiation in both the shortwave (.28–2.5 μm) and longwave (8–14 μm) regions of the electromagnetic spectrum. The balance of these four fluxes is summarized by the net radiation (sometimes called the net allwave radiation), which can be written:

$$R_n = R_S\downarrow - R_S\uparrow + R_L\downarrow - R_L\uparrow \qquad (1)$$

where;

R_n = net (allwave) radiation,
$R_S\downarrow$ = incoming shortwave radiation,
$R_S\uparrow$ = outgoing shortwave radiation,
$R_L\downarrow$ = incoming longwave radiation,
$R_L\uparrow$ = outgoing longwave radiation.

Outgoing shortwave radiation is a function of the surface albedo (α), and the outgoing longwave flux is controlled by surface temperature (T) and emissivity (ϵ). Thus, Equation (1) can be rewritten in a form that emphasizes these physical characteristics of the surface:

$$R_n = (1 - \alpha)\, R_S\downarrow + R_L\downarrow - \epsilon\sigma T^4. \qquad (2)$$

The net radiation is significant because it represents the amount of energy available to drive radiation-mediated processes such as evapotranspiration and sensible heat exchange. Elements of the carbon cycle, such as plant metabolism and photosynthesis, also derive their energy from net radiation (Rosenberg et al. 1983). A thorough understanding of climatological, hydrologic, and biophysical processes at the surface must therefore include consideration of the disposition of radiation.

Spatial Heterogeneity and the Radiation Budget

It has long been realized that spatial variations in surface radiation budget components will have significant effects on variability of available energy (e.g., Ångstrom 1925). Many energy budget studies to date, however, have relied on net radiation measurements made only at a single site. This approach assumes that the underlying surface is uniform and that point measurements are therefore representative of the entire study area. For relatively homogenous cover types such as water, bare soil, crop, or pasture, this assumption may not be unreasonable. In a landscape with a more irregular pattern of surface cover, however, a single measurement may be inadequate. Pielke and Avissar (1990) and Bouwman (1990) discussed the influence of landscape heterogeneity and surface cover change on local and regional climates. They found that landscape heterogeneity results in considerable contrast in the amount of radiation absorbed, reradiated, and partitioned into various energy sinks within the canopy and substrate, thus producing climatic variation. Although landscape variation at smaller spatial scales were not explicitly considered, it seems reasonable that similar principles would apply across scales.

Investigations of the variability of the radiation budget at smaller spatial scales include Federer (1968), who measured the net radiation at six sites over a hardwood forest with a goal of determining the intensity of sampling necessary to adequately capture variability and determine a meaningful average value. Gay (1979) contrasted the radiation budgets for four surface types (desert, meadow, forest, and marsh). He found significant variation in the fraction of incoming radiation converted into net radiation, a factor that would result in microclimatic variation even under the same incoming radiation conditions. Other studies have concentrated on factors influencing the variability of individual components of the radiation budget, especially surface albedo. Stewart (1971) and Kriebel (1979) examined the effect of varying solar irradiance on albedo in pine forest and savannah, respectively. Burglund and Mace (1973) considered seasonal effects on the albedo of spruce forest and sphagnum-sedge bog. Petzold and Rencz (1975) and Goodin and Isard (1989) studied the albedo of tundra in subarctic and alpine environments. However, with the exception of the latter study, none of these expressly considered spatial variation.

Heterogeneity and the Radiation Budget of Wetlands

Despite their role in a number of climatic, hydrologic, and biological processes (Gannon et al. 1978), few studies have considered the radiation budgets of wetlands. Crabtree and Kjerfve (1978) measured the radiation budget of coastal salt marsh, but studies for other wetland types are scarce. This is somewhat surprising, since most ecological processes within wetlands are related in some way to the radiation budget. Analysis of the radiation budget characteristics of wetlands is complicated by surface heterogeneity. Wetlands are a mosaic of contrasting vegetation and substrate conditions and thus are subject to the effects of surface heterogeneity described above. Modeling the receipt, flow, and ultimate disposition of energy within wetland ecosystems may thus depend on understanding the extent and impact of variation in surface cover on the radiation budget.

Modeling Net Radiation

In addition to their climatic significance, elements of the surface radiation budget have applications in other areas. For example, many commonly used methods of estimating evapotranspiration, such as the Penman equation, require net radiation as an input (Mitsch and Gosselink 1993). Since incoming solar radiation is being measured at an increasingly large number of stations, while net radiation is generally measured at only a few (often temporary) sites, a method for calculating R_n using only estimates of incoming solar radiation would be of considerable value for calculation of water loss from lakes and wetlands. A number of researchers have noted a strong linear relationship between net radiation and incoming solar radiation, and some have used regression techniques to derive empirical models (see Rosenberg *et al,* 1983 for a review of some of these models):

$$R_n = aR_S + b \tag{3}$$

These models are apparently quite successful at predicting net radiation, yielding correlation coefficients ranging from 0.95 to 0.99. However, Gay (1971) criticized the use of such simple empirical models, pointing out that, despite the high correlation and standard error reported for these models, they do not account for longwave energy exchange and their coefficients do not permit physical interpretation. He suggests a modification that accounts for the relationship between $R_S\downarrow$ and $R_L\uparrow$:

$$R_n = (1 + \lambda)\, R_S{}^* + R_{Lo}{}^* \tag{4}$$

where:

λ = longwave exchange coefficient (a-1, where a is the slope coefficient from Equation 1),
$R_S{}^*$ = $(1\text{-}\alpha)R_S\downarrow$,
$R_{LO}{}^*$ = the estimated value of R_n when $R_S\downarrow = 0$.

Although still empirical in nature, Gay's model has the advantage of producing coefficients that can be interpreted physically and compared to other sites.

Our purpose in this study was to examine some of the effects of landscape heterogeneity on the spatial variability and contrast in the radiation microclimate of a wetland in the Nebraska Sandhills and to examine the effects of this heterogeneity on modeled estimates of net radiation. The Sandhills region of Nebraska is the largest dune field in North America but consists of sand dunes stabilized by a thin veneer of grassy vegetation. Hence, the dunes are immobile except in response to environmental disturbance (Swinehart 1984, Novacek 1989). The Sandhills overlie the maximum saturated thickness of the Ogallala formation, and ground water is abundant and close to the surface. Where deep interdunal depressions extend below the water table, ground water collects on the surface, forming the Sandhills lakes. There are over 1000 permanent lakes scattered throughout the region, accounting for about 558,000 ha (approximately 10%) of the surface area of the Sandhills (Mitsch and Gosselink 1993). These lakes are wetland systems, consisting of open water, marsh, and meadow areas fed by groundwater discharge. Generally, marsh occurs as a fringe surrounding the open water and as vegetated "islands" within it. Height of emergent vegetation varies with depth of water below the canopy. In deeper water, a high marsh characterized by broadleaf cattail (*Typha latifolia* L.), common reed (*Phragmites communis* Trin), and hardstem bulrush (*Scirpus acutus* Muhl.) occurs, while in shallower water, a low marsh consisting mainly of sedge (*Carex nebraskensis* Dewey), smartweed (*Polygonum lapathifolium* L.), and arrowhead (*Sagittaria cuneata* Sheld.) is found. Vegetation in the subirrigated meadow consists mainly of mixed grass prairie species such as blue joint (*Agropyron smithii* Rydb.), big bluestem (*Andropogon gerardii* Vit.), Indian grass (*Sorghastrum nutans* L.), and switch grass (*Panicum virgatum* L.).

The Sandhills lakes and their associated wetlands were chosen for study because climatically they stand in sharp contrast to their surroundings, which have substantially less soil moisture and sparse vegetation cover. In addition, the Sandhills are embedded within a region that is known for its sensitivity to climatic variation. The results of many General Circulation Model (GCM) experiments indicate severe impacts on the North American Great Plains associated with an enhanced greenhouse effect due to anthropogenic trace gas emission (Hanson et al. 1988). The location of the Sandhills, overlying the Ogallala aquifer and along the North American flyway, raises the possibility of substantial impact on the role of these lakes in both waterfowl ecology and regional hydrology if the climatic impacts of trace gas emissions forecast by GCMs are realized. Understanding and predicting the potential impact of climate or other environmental change on the hydrology and ecology of the Sandhills wetlands depends on first understanding some basic elements of their radiation regime.

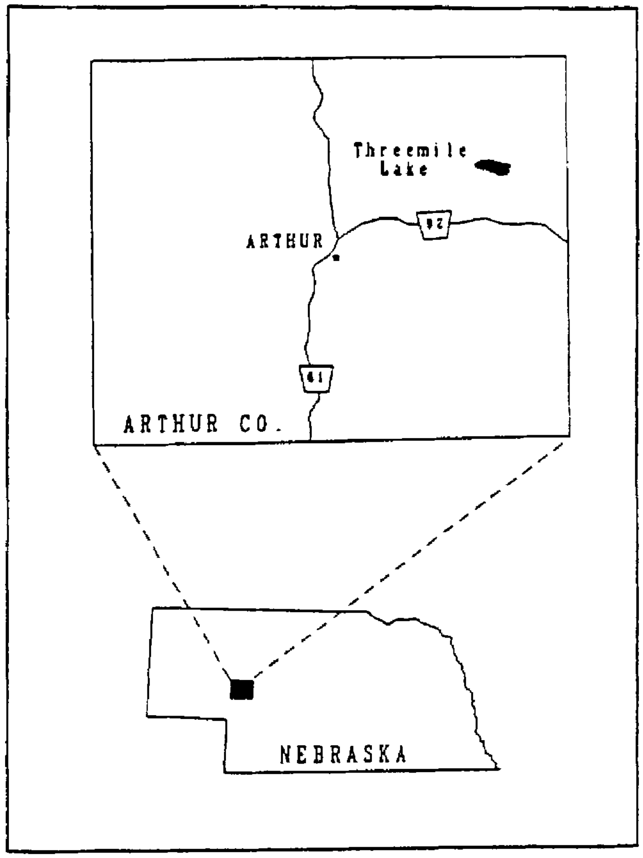

Figure 1. Map of the study site in the Nebraska Sandhills.

We will address these problems by considering three related questions: 1) can the radiation regime of the entire wetland be treated as a homogenous unit, or must it be treated as a series of subsystems, 2) if the radiation regime is not homogenous, what factors are most significant in determining its spatial heterogeneity, and 3) can methods be developed to accurately estimate R_n with minimal data input, given the heterogenous nature of the surface cover?

STUDY SITE AND METHODOLOGY

The Study Site

Threemile Lake, located in northeast Arthur county, was chosen as the study site for this research (see Figure 1). Threemile Lake is in most ways a typical Sandhills lake. It lies in a flat-floored valley between vegetated dunes that parallel each other trending east-west. Local relief from the valley floor to dune crest is approximately 50 meters. Threemile Lake features extensive areas of open water as well as subirrigated meadow and marsh. The lake lies entirely on a cattle ranch, and the lake and wetlands serve as an important source of feed and water for the ranch livestock. This management practice results in a much sharper transition between the various subsystems (particularly the meadow and marsh) than would normally occur in an undisturbed Sandhills wetland. Meadow vegetation varied from about 0.25 to 0.35 m in height over the course of the growing season. Midseason mowing reduced canopy heights to about 0.1 m. Low marsh vegetation varied from about 0.75 to 1.0 m (depending on species) and did not show much height variation over the measurement period. The high marsh varied from about 1.0 to 1.2 m early in the measurement period to as much as 2.0 m near the end.

Measurements

Fixed sites. Stationary measurement stations consisting of a REBS Q*6 net radiometer, for measuring net radiation, and an inverted Eppley model 8–48 pyranometer, for measuring reflected shortwave radiation, were established over each of the wetland subsystems. At one of these sites, a LI-COR 200SB silicon-cell pyranometer and an Eppley PIR pyrgeometer were used to measure the incoming terms of the radiation budget. The LI-COR pyranometer was used to measure incoming solar radiation in this research because no additional Eppley instruments were available and because the sensor type precludes use in the inverted position. All instruments were factory-calibrated and intercompared for accuracy prior to installation at the field site. The REBS net radiometers have been shown to be more accurate in daytime than at night; however, comparison with other commonly used net radiometers under field conditions has shown them to be accurate to an RMS error ranging from 15 and 35 Wm^{-2} (Fields *et al.* 1992).

All instruments at the fixed stations were interfaced to LI-COR LI-1000 dataloggers, which recorded average hourly values of each flux. The fixed stations were in place between 2 June and 22 October 1992 and between 6 June and 9 September 1993. Instruments to measure the net and outgoing radiation terms were originally mounted so that the sensors were 2.0 m above the level of the substrate and between 1.5 and 1.0 m above the canopy top. Later in the season, the instruments mounted over the marsh surfaces were raised so they cleared the canopy top by about 1.0 m at all times. Surface albedo values were determined by calculating the ratio between the incoming and outgoing shortwave radiation measured at each site.

During the 1992 field season, the fixed stations were installed over open water, marsh, and subirrigated meadow sites. However, it was noted during this phase of the project that the marsh itself had some internal variation. Therefore, during the 1993 field season, the three stations were installed over low marsh, high marsh, and meadow sites. Under this stratification scheme, the marsh site from the 1992 data corresponded to high marsh. Availability of instruments precluded the installation of more than three stations.

Table 1. Summary of mean diurnal totals for radiation budget components at each site for both field seasons.[1]

Site	$R_S\downarrow$	$R_L\downarrow$	$R_S\uparrow$	$R_L\uparrow$	R_n	α
High Marsh	24.55	27.48	3.74	31.19	17.53	0.152
Low Marsh	24.55	27.48	4.35	31.10	16.78	0.178
Meadow	24.55	27.48	5.02	33.09	14.08	0.205
Water	24.55	27.48	1.78	29.12	20.43	0.073

[1] Units are MJ m^{-2} day^{-1}.

Spot measurements. In addition to these fixed measurement stations, spot measurements of the outgoing terms of the radiation budget were made at four times during the 1992 field season (16–18 June, 14–15 July, 19–20 August, and 28–29 September) using an inverted Eppley pyranometer and an Everest Interscience infrared thermometer attached to a portable yoke. The data collection procedure for spot measurement consisted of measuring along a transect that included expanses of subirrigated meadow, high and low marsh, and open water. Samples were taken about every 15 m along the transect by suspending and leveling the instrumented yoke over the measurement site, allowing approximately one minute for the instruments to equilibrate, then recording data using the LI-COR datalogger in command-recording mode. Transects were conducted at one hour intervals beginning at 0900 LST and ending at about 1500 LST. Each transect required about twenty minutes to complete. Surface temperature measurements were converted to emitted longwave radiation using the Stefan-Boltzmann equation with emissivity estimates obtained from Gates (1983). Spot measurements were coordinated with fixed instruments measuring the incoming fluxes so that all five terms of the radiation budget were accounted for.

RESULTS

Effect of Surface Heterogeneity on Net Radiation

Mean total daily values of all radiation budgets are given in Table 1. The mean diurnal course for radiation budgets at the four sites clearly shows the influence of incoming solar radiation on the daily course of net radiation, with both fluxes showing daytime patterns symmetric around local solar noon (see Figure 2). Outgoing shortwave radiation, a function of surface albedo, also "peaks" at the same time. Incoming and emitted longwave radiation do not show such a symmetric pattern.

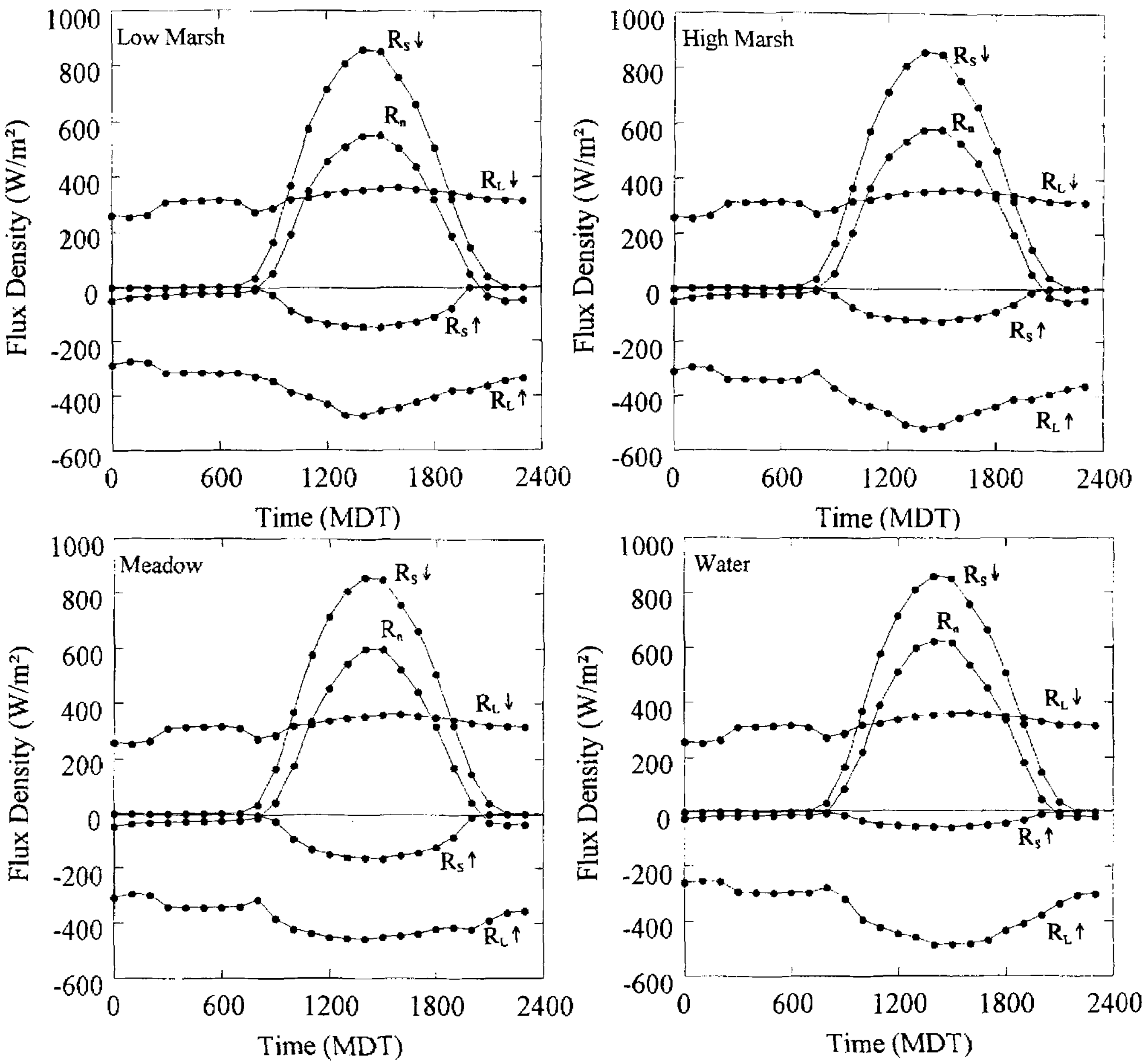

Figure 2. Mean diurnal radiation budgets for the original four cover types. Data are from the 1992 and 1993 field seasons.

Simple inspection of the data in Figure 2 does not indicate whether the radiation budgets of the four sites are distinct from each other, so additional quantitative analyses were performed. Fixed effects one-way analysis of variance was performed on averaged daily net radiation values to test for significant variations within each season's data (note, all statistical analyses in this study were performed using the SYSTAT package, Systat, Inc. 1992). Net radiation was used because it effectively "summarizes" the entire radiation budget. Results from the 1992 data indicate significant variation within the data ($F_{70,2}$=11.51, P<0.001). Differences between individual cover types were evaluated using Tukey's Honestly Significant Difference (HSD) comparison test. Tukey's method uses pairwise comparisons of the means and mean standard error for each cover type to compute a probability of association for each pair of cover types. It is intended as a post-hoc technique for clarification of the results of ANOVA (Kleinbaum and Kupper 1978). Probability values calculated using Tukey's method support the conclusion that net radiation at all three sites are separable (see Table 2). A similar analysis of the 1993 data once again revealed variation, although not as significant as that of the 1992 data ($F_{52,2}$=3.889, P=0.022). Pairwise comparisons for these data show a strong relationship

Table 2. Pairwise comparison probabilities for three subsystems—1992 net radiation data.

	Marsh	Meadow	Water
Marsh	1.000		
Meadow	0.011	1.000	
Water	0.004	0.000	1.000

between high and low marsh, and a smaller but still nearly significant similarity between low marsh and meadow (Table 3). Apparently, the initial stratification of the wetland into three general subsystems resulted in three statistically distinct sites, while the more detailed stratification of the vegetated sites used in the 1993 data did not. As a final test, both seasons' data sets were aggregated and reanalyzed. Once again, significant difference in the whole data set was observed ($F_{122,3}$=7.969, P<0.001), with pairwise comparison indicating strong resemblance between high and low marsh and between low marsh and meadow (Table 4).

It is apparent that there is significant variation of net radiation within the study site. The net radiation, however, is a composite term that represents the balance of four component fluxes in two separate regions of the electromagnetic spectrum (see Equation 1). All these components are to some extent interrelated, yet consideration of each component flux separately will aid understanding the overall variability of radiation budgets within the wetland. In the absence of topographic variability, the incoming short and longwave radiation streams are principally controlled by the flux density of solar radiation arriving at the top of the atmosphere (in the case of the shortwave stream), as well as by atmospheric characteristics such as water vapor and aerosol content, temperature, and cloud cover. All of these factors are spatially variable, but their variation generally occurs at regional or synoptic scales, rather than the local scale. Since the terrain within the study site is essentially flat, the incoming components of the radiation budget are not expected to show great spatial variability over a study area of this size. We must therefore concentrate on the outgoing components of the radiation budget in order to determine what factors control the spatial variability of net radiation.

The outgoing fluxes are principally controlled by the surface properties of albedo and temperature. Data on these two surface properties from the aforementioned spot measurements were analyzed to determine their role in controlling the spatial distribution of net radiation. Results from ANOVA using albedo as the dependent variable show highly significant variation within the data set ($F_{364,3}$=115.91, P ≪ 0.001). The very high F-ratio for this test reflects both the great contrasts between and low variance within each site, especially the water. Most importantly, though, post-hoc pairwise comparison using Tukey's HSD shows that all four subsystems are statistically separable from one another (Table 5). Analysis of variance results for emitted longwave radiation are also significant ($F_{364,3}$=38.39, P < 0.001), but the results of the pairwise comparison indicate that the low and high marsh subsystems have mean values of emitted longwave radiation that cannot be statistically separated (Table 6). This not only explains the previous analysis of R_n (which linked the two marsh subsystems), but it also suggests that emitted longwave radiation plays an important role in determining the spatial structure of the radiation budget.

Table 3. Pairwise comparison probabilities for three subsystems—1993 net radiation data.

	High Marsh	Low Marsh	Meadow
High Marsh	1.000		
Low Marsh	0.332	1.000	
Meadow	0.016	0.045	1.000

Table 4. Pairwise comparison probabilities for the 1992 and 1993 net radiation datasets.

	High Marsh	Low Marsh	Meadow	Water
High Marsh	1.000			
Low Marsh	0.344	1.000		
Meadow	0.007	0.258	1.000	
Water	0.014	0.004	0.000	1.000

Modeled Net Radiation

From the foregoing, it is apparent that the Sandhills wetland system can be subdivided into three distinct subsystems (marsh, meadow, and open water). We now focus on estimating net radiation, using the three subsystems as an organizing framework. Equations (3) and (4) were fitted to the station data for the three distinct cover types (marsh, meadow, and water) which emerged from the previous analysis. Measures of as-

Table 5. Pairwise comparison probabilities for albedo data from spot measurements.

	High Marsh	Low Marsh	Meadow	Water
High Marsh	1.000			
Low Marsh	0.000	1.000		
Meadow	0.000	0.000	1.000	
Water	0.000	0.000	0.000	1.000

Table 6. Pairwise comparison probabilities for emitted longwave radiation data from spot measurements.

	High Marsh	Low Marsh	Meadow	Water
High Marsh	1.000			
Low Marsh	0.761	1.000		
Meadow	0.002	0.001	1.000	
Water	0.014	0.000	0.000	1.000

sociation (Table 7) show the strength and significance of the linear relationship between these variables, with Equation (4) yielding a slightly better fit than the simple linear model Equation (3).

ANALYSIS AND DISCUSSION

Heterogeneity and the Radiation Budget

It is apparent from our results that the Sandhills lakes and wetlands contain significant internal variation in radiation regimes. However, the variation is not as complex as was originally thought. In particular, the similarity between the two marsh types was surprising, given the morphological differences between them. Physically, the differences in net radiation between the wetland subsystems may be due to a number of factors, but simple height of the vegetation canopy readily explains some of the variation. A cross-section of canopy heights through the study site reveals a continuum ranging from the lower-canopied grasses in the subirrigated meadow, through progressively taller vegetation in the low and high marsh, terminating at the open water through which no vegetation protrudes. Decker (1959) noted a positive relationship between canopy height and net radiation, which is similar to the pattern observed here for the vegetated surfaces. The marsh vegetation is considerably taller than the meadow grasses and has higher net radiation values. This pattern can also be noted within the marsh where, despite the lack of statistically significant separability, the two subsystems also conform to this relationship, with the low marsh having the lower net radiation values (see Table 1). Albedo plays a significant role in determining this pattern. Oke (1987) noted that internal reflection within a taller vegetation canopy forms a better "light trap", thus reducing albedo. Lower albedo results in a smaller stream of outgoing shortwave radiation and, thus, higher net radiation (see Equation 2).

Explanation of R_n differences based on vegetation height cannot, of course, be extended to the open water system. However, surface albedo seems to be an important discriminant for this cover type, as well. The albedo values for water are much less than for any of the vegetated systems. The lower surface albedo for water can be attributed mainly to its light absorption properties. Water reflects virtually no near-infrared radiation, and its visible reflectance is also very low except at extreme solar zenith angles. Despite the shallowness and turbidity of the water at the site, comparison of our values to published values of water albedo (e.g., Oke 1987) indicate similarity to other water bodies.

Although contrasting albedo can explain much of the variability in these data, it alone is insufficient as an explanation of the spatial variability of the radiation budget in the study site. Evidence for this lies in the very strong statistical variability of albedo between the four original subsystems, a variability not observed in the net radiation. This is especially evident within the marsh, where the net radiation is not separable despite the contrast in albedo. The explanation for this must lie in the longwave radiation balance.

Unlike albedo, the thermal regime of the wetland subsystems does not vary greatly. Apparently, the similarity of the longwave radiation exchange masks much of the variability resulting from contrasts in the shortwave balance, thus emerging as a "homogenizing" influence. This is especially true within the marsh, where these data show a very strong relationship between the mean emitted longwave radiation in the high and low subsystems (Table 6). This similarity is enough to override the large differences in the shortwave radiation balance between the two cover types. The pattern of longwave balance can be explained by the influence of vegetation cover, standing water, and soil moisture on the disposition of available energy. The open water has no vegetation cover, so evaporation should proceed at or very near the potential rate. Consumption of available energy by latent heat exchange, with little remaining for conversion to sensible heat, means that air and surface temperature for the water must be lower, and indeed, the mean emitted longwave radiation for water is considerably less than

Table 7. Results of empirical modeling of net radiation using equations (3) and (4).

Subsystem	λ	Equation (4)	R^2	Equation (3)	R^2
Marsh	−.102	$R_n = 0.898R_S^* - 21.59$	95.5	$R_n = 0.779R_S\downarrow - 31.3$	93.6
Meadow	−.131	$R_n = 0.869R_S^* - 14.79$	94.1	$R_n = 0.713R_S\downarrow - 32.1$	92.2
Water	−.087	$R_n = 0.913R_S^* - 10.77$	92.7	$R_n = 0.717R_S\downarrow - 34.2$	90.1

any of the vegetated surfaces. There is much less difference between the vegetated sites. However, the meadow site, with no standing water, has a higher surface temperature than either marsh site. Even though the meadow grasses are well-supplied with water in the root zone, and are thus cooled by evapotranspiration, solar radiation must be penetrating through the canopy to the relatively dry substrate, where it is converted to sensible heat. The hydrophytic vegetation in the marsh also has a saturated root zone, but in this case solar radiation penetrating the canopy will be converted to latent rather than sensible heat because of evaporation of the water beneath the canopy. Thus, overall surface temperatures (and emitted longwave radiation) will be greater in the meadow than the marsh. Without more detailed measurement of both the radiation regime within the canopy and of the entire energy budget, it is impossible to confirm these explanations or quantify their actual impact.

Net Radiation Modeling

Analysis of the results of the empirical modeling of net radiation support many of the conclusions drawn above. Gay (1971) found that models such as Equation (4) are preferable to simple linear models because they yield coefficients that can be physically interpreted and compared to other ecosystems. In particular, the λ-values yield insight into the thermal properties of the three subsystems. A λ-value less than zero indicates a surface where shortwave radiation is increasing more rapidly than the fraction of available energy partitioned to evapotranspiration. This surplus energy must therefore be partitioned to sensible heat exchange. Thus, the λ-value forms an index of conversion efficiency between incident shortwave radiation and surface temperature. The higher the λ-value, the greater the temperature increase associated with an increase in R_S^*. Considered in this light, the λ-values for the three subsystems readily fall into a logical progression. Open water has the smallest absolute value of λ, corresponding to a surface with a greater portion of incident solar radiation partitioned into the latent heat exchange, and thus less surface heating. The marsh, with a saturated root zone and standing water beneath the canopy, has an intermediate λ-value. Meadow, which is the driest of the subsystems due to the lack of standing water, has the largest fraction of available energy converted to sensible heat. These results can be directly compared to the previous discussion of surface temperature and emitted longwave radiation, where they further support the importance of the longwave budget in determining the overall net radiation.

CONCLUSIONS

This analysis has shown that, despite the heterogeneity apparent in vegetation, the radiation regime of the Sandhills wetland is simpler than it would appear at first glance. This is particularly true in the marsh, where the efficiency with which incoming radiation is converted to net radiation shows little variation, despite significant difference in absorbed shortwave radiation. The lack of strong contrast between the radiation budgets of the various subsystems is attributable to similarity in longwave energy exchange. This information provides a framework for further consideration of the role of radiation in the ecological functioning of the Sandhills wetland system as a whole. It also provides a basis for comparison of the Sandhills lakes with other wetland types, as well as with non-wetland ecosystems. Such comparisons can shed further light on the overall effects of surface heterogeneity on climate.

Our study also demonstrates the utility of empirical models of net radiation. However, use of these models in heterogenous landscapes must be constrained by the fact that each cover type within the landscape has unique properties, requiring an explicit form of the model. Recognizing this, such models can be applied in a number of ways, including computing water loss due to evapotranspiration and providing the net radiation data necessary for latent and sensible heat computation in models of energy flow in wetland ecosystems (Crabtree and Kjerfve 1976). Of course, the coefficients presented here are specific to this site; however, our results demonstrate the feasibility of the methodology. Use of Gay's form of the regression model provides the additional benefit of deriving physically interpretable empirical coefficients, further facilitating comparison with other sites.

Several research questions arise from these results. Although our findings suggest some of the causes of spatial heterogeneity in the radiation budget, more detailed explanation of the mechanisms producing the variation are needed. Detailed study of canopy architecture (and its effect on penetration of incoming radiation), canopy temperature distribution, subcanopy water or surface temperature, depth of transpiring foliage, and phenological development would offer additional insight into the physical processes of radiation exchange and differentiation of radiation climate within the various subsystems. Such findings would also contribute to a more general understanding of radiation exchange characteristics at the Earth's surface.

Investigation of the surface radiation regime is also an important first step toward understanding the entire energy balance of the Sandhills wetlands. Our results show how the various subsystems differ in efficiency of converting incoming radiation to available energy. Further study of the partitioning of this available energy would shed light on the relative importance of various energy sinks at the surface. Such energy exchange characteristics are a significant factor in differentiation of ecosystems (Miller 1981). Thus, understanding them would further assist both ecologists and climatologists in understanding the unique aspects of the Sandhills environment.

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