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 (0.28–2.5 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:

\[ R_n = R_s\downarrow - R_s\uparrow + R_l\downarrow - R_l\uparrow \quad (1) \]

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 (\( \alpha \)), and the outgoing longwave flux is controlled by surface temperature (\( T \)) and emissivity (\( \varepsilon \)). Thus, Equation (1) can be rewritten in a form that emphasizes these physical characteristics of the surface:

\[ R_n = (1 - \varepsilon) R_s\downarrow + R_l\downarrow - \varepsilon \sigma T^4. \quad (2) \]

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 signif-
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 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 Renz (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 Rs 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):

\[ R_n = a R_s + b \]  

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 \( R_n \uparrow \):

\[ R_n = (1 + \lambda) R_s^* + R_{Lo}^* \]  

where:

\[ \lambda = \text{longwave exchange coefficient (} a-1, \text{ where } a \text{ is the slope coefficient from Equation 1),} \]

\[ R_s^* = (1-a)R_s \downarrow, \]

\[ R_{Lo}^* = \text{the estimated value of } R_s \text{ when } R_s \downarrow = 0. \]

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...