Estimating Evapotranspiration within the Colorado Alpine Tundra with Landsat Thematic Mapper

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ABSTRACT

Evapotranspiration (ET) is a key element in climate related studies on all spatial and temporal scales. Recent studies have shown that ET can be estimated with some degree of precision from meteorological satellites, over flat terrain, using semi-empirical and analytical models. However, no method has been proposed in order to derive this parameter in mountainous terrain by combining remotely sensed imagery with ancillary data. This can be explained in part by the difficulties in estimating many of the relevant parameters which control ET rates, namely the radiation balance, wind speed and the aerodynamic resistance. In this paper, an approach is proposed for estimating ET in a high relief environment with Landsat Thematic Mapper imagery and digital terrain data. Preliminary results in the computation of the net shortwave radiation in the alpine tundra of Niwot Ridge (Colorado Front Range, U.S.A.) suggest possible solutions to the problem of estimating of ET in mountainous terrain using remotely sensed data.

Key Words: Evapotranspiration, net radiation, alpine tundra, Landsat Thematic Mapper, digital terrain data.

INTRODUCTION

Developments in the study of the radiation balance and energy balance of the 1950s - 1960s (e.g. Pennman, 1956) have enabled, among other things, to establish relationships between evapotranspiration (ET) and surface temperature. Equations used to estimate ET include different parameterizations based on the type of evaporating system (land cover type), its thermodynamical state (temperature and moisture), its aerodynamical behaviour (roughness and structure) and the atmospheric state (temperature, moisture, wind and stability conditions) (Becker et al., 1987). These parameterizations depend on the time and space scales at which the measurements are made, because of the non-linearity of the processes involved and the heterogeneity of the earth's surface characteristics.

Models which were solely based on point measurements can now benefit from the spatial and temporal resolution offered by current meteorological and earth resources satellites. Satellite-borne sensors that record radiation reflected and emitted from the earth's surface are currently used in order to derive the surface parameters necessary for the determination of regional ET. Indeed, recent studies have shown that ET can be determined from complex physical models using satellite imagery (e.g. Meteosat and HCMM) and meteorological parameters (air temperature and moisture, wind speed, etc.). These range from statistical semi-empirical formulations (Idso et al., 1975; Séguin et Itier, 1983) to analytical and numerical methods based on sophisticated physical models of heat and mass transfer (Carlson et al., 1981; Taconet et al., 1986; Abdellaoui et al., 1986). Results of these studies suggest that at the regional scale the parameterizations reproduce the general behaviour of experimental data taken at local scale (field measurements), but representative of a larger area (over flat terrain).

In mountainous terrain, however, point measurements are generally not adequate for representing the parameters required for obtaining reasonable estimates of ET over large areas. The nature of mountain terrain sets up such a variety of local weather conditions such that any point measurement is likely to be representative of only a limited range of sites. Here, point measurements of wind speed, air moisture and temperature need to be extended over surfaces of varying slope and aspect. This of course adds more complexity to the problem of estimating ET from remotely sensed data. Models based on extensive field campaigns (local scale) are giving us new insights into the determination of meteorological parameters over rugged terrain. In a recent study, Isard and Belding (1988) have shown that reasonable estimates of ET (local scale) could be obtained from the mid-latitude alpine tundra of Colorado provided that daily inputs of surface net radiation and ground heat flux were available. This paper briefly describes ongoing work towards the development of a model for estimating ET from the alpine tundra of Colorado using Landsat Thematic Mapper (TM) imagery and digital terrain data.

METHODS

Study Area

The study area is located in the Indian Peaks section of the Colorado Rocky Mountain Front Range, and is one of the University of Colorado Long-term Ecological

Research sites. On Niwot Ridge, insolation, wind, precipitation, and topography interact to produce abrupt environmental changes and thereby control the distribution of alpine tundra vegetation (Figure 1). The steep topographic-moisture gradients found on Niwot Ridge are created by strong westerly winds that redistribute freshly fallen snow, creating deep snowfields on leeward slopes while leaving adjacent windward slopes and ridge crests snow free. During the snowmelt period (May to July), snowfields supply meltwater to areas directly downslope. Wind and insolation interact to govern ET through control over the water vapour gradient and rate of vapour transfer between the earth's surface and lower atmosphere (Isard, 1986).

Model Description

Background In order to develop a model for estimating ET daily from the alpine tundra using remotely sensed data, there is a need to first investigate the parameters that control ET on both local and regional scales, and then determine which of these are amenable to measurement by remote sensing. It is however beyond the scope of this paper to evaluate the importance of each parameter individually. Algorithms for estimating ET from remotely sensed data and the parameters that complicate its determination have been described elsewhere (Becker and al., 1987).

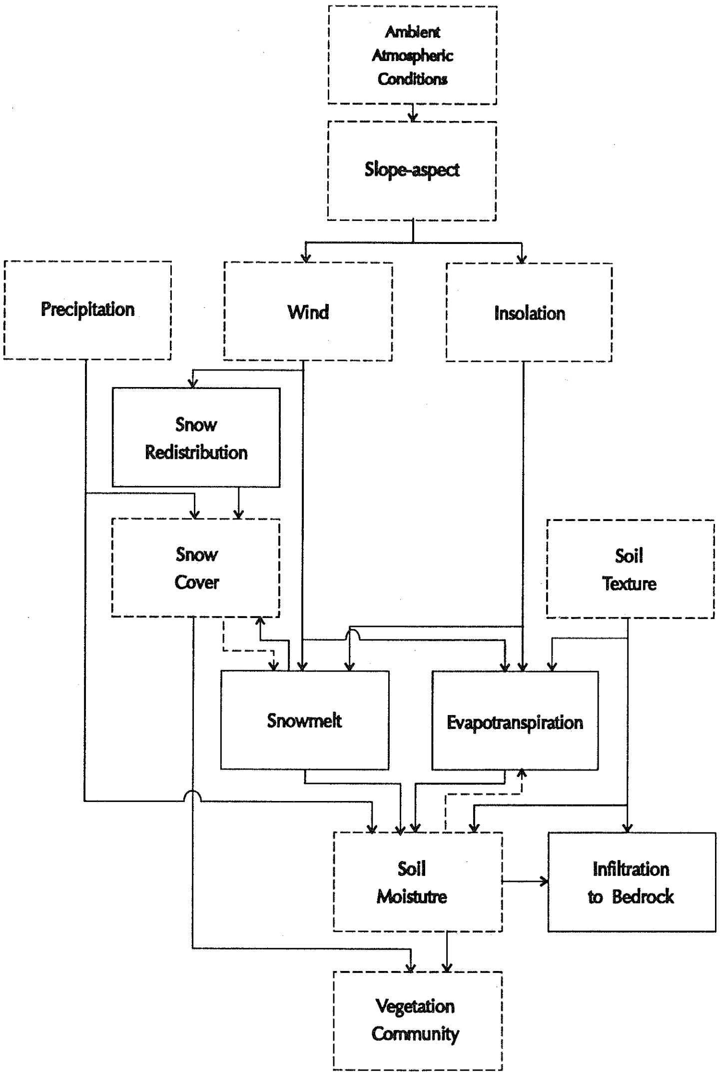

Figure 1. Conceptual model of moisture dynamics in the mid-latitude alpine tundra (from Isard, 1986).

Two factors that are of primary concern in the estimation of ET from the alpine tundra are wind speed, which is necessary for obtaining estimates of surface roughness, and measurements of surface net radiation. At the locale scale (i.e. field measurements), Isard and Belding (1988) have shown that reasonable estimates of ET could be obtained from the dry alpine meadows of Niwot Ridge using an indirect technique that utilizes daily averages of net radiation (Rn) and ground heat flux (G) (index of agreement of 0.90). This regression procedure, of the form ET = a + b(Rn-G), replaces the aerodynamic vapour flux term with a constant and a multiplier. Using insolation (K↓) as a surrogate for the quantity of available energy in a regression format, these authors obtained an index of agreement value of 0.80. Results of this study are of particular interest to remote sensing estimates of ET (regional scale), since parameters such as Rn may be calculated from remote sensing means over rugged terrain.

Individual Components of the Radiation Balance Equation The radiation balance equation can be written as

$$Rn = K\downarrow\ (1-\alpha) + L\downarrow - L\uparrow \tag{1}$$

where K↓ is the shortwave irradiance (insolation), α is the surface albedo, L↓ is the longwave irradiance (atmospheric emittance), and L↑ is the surface thermal exitance.

In the model, both downward components (W m^{-2}) are computed for non-obstructed horizontal surfaces using a modified implementation of the two-stream radiative transfer formulation of Zdunkowski et al. (1982). In sloping terrain insolation is

$$K\downarrow[z] = \phi\ S_h[z]\ (\cos i / \cos i_h) + D_h[z]\ \{k'[z]\ (\cos i / \cos i_h) + 0.5\ (1 - k'[z])(1 + \cos s)\} + 0.5\ \alpha\ K_h[z]\ (1 - \cos s) \tag{2}$$

In (2), [z] indicates that the value of the parameter varies with height. Briefly, S_h defines the direct irradiance to an unobstructed horizontal surface, computed from the two-stream model. The variable i_h is the angle of incidence to a horizontal surface, and is simply computed as the cosine of the solar zenith angle. Values of D_h (diffuse sky irradiance) and K_h (total irradiance) for unobstructed horizontal surfaces are also derived from the two-stream model. The parameter k' is the anisotropy index which is utilized to separate diffuse sky irradiance into isotropic and circumsolar components. Parameters s, i, and α are the slope, angle of incidence, regional albedo, respectively. Variable ϕ indicates whether the surface is in shadow (ϕ=0) due to topographic obstructions from surrounding terrain. Terrain related parameters are derived using a USGS 30-meter digital elevation model.

Using results of the two-stream model, the longwave irradiance (L↓) is calculated as

$$L\downarrow[z] = L\downarrow_h[z]\ V_f + (\varepsilon_s\ \sigma\ T_s^4)\ (1-V_f) \tag{3}$$

where $L\downarrow_h[z]$ is the longwave irradiance on an unobstructed horizontal surface, V_f is the sky view factor, ε_s is the emissivity of the surface, σ is the Stefan Boltzman constant (5.67 x 10^{-8} W m^{-2} K^{-4}), T_s is the temperature of the surface. The first portion of equation (3) represents the portion of the longwave radiation emitted by the atmosphere while the second portion is the longwave emission from the surrounding terrain.

The outgoing fluxes α and L↑ are derived using Landsat TM reflective and thermal bands. Albedo for a vegetated surface is (Duguay and LeDrew, 1992)

$$\alpha = 0.526(\rho[TM2]) + 0.362(\rho[TM4]) + 0.112(\rho[TM7]) \tag{4}$$

For non-vegetated surfaces (excluding snow), the albedo is

$$\alpha = 0.526(\rho[TM2]) + 0.474(\rho[TM4]) \tag{5}$$

In (2) and (3), ρ is the surface reflectance derived from satellite data. Under a lambertian assumption

$$\rho[i] = \pi\ (L[i] - L_p[i,z]) / (T_v[i,z]\ E[i,z]) \tag{6}$$

where L[i] is the radiance reaching the sensor for a given satellite band [i], $L_p[i,z]$ is the atmospheric path radiance for a given band [i] at altitude [z], $T_v[i,z]$ is the vertical atmospheric transmission for a given band [i] from a surface at altitude [z] to the sensor, and E[i,z] is the solar irradiance, direct plus diffuse, on a sloping surface at altitude [z]. In this equation, $L_p[i,z]$, $T_v[i,z]$, and E[i,z] are calculated from the radiative transfer code LOWTRAN 7.

Finally, under clear skies, the surface thermal exitance is determined through the use of the Stefan-Boltzman relationship

$$L\uparrow = \varepsilon_s\ \sigma\ T_s^4 \tag{7}$$

It has been shown, that properly calibrated Landsat TM thermal infrared data, collected under clear sky conditions, can be used to obtain accurate temperature measurements without the need for atmospheric corrections (Bartolucci et al., 1988). This is because under clear skies, the atmospherically attenuated target radiance appears to be compensated by the path radiance. In (7), surface brightness temperature measurements are derived from TM thermal Band 6 using the equation (Schott and Volchock, 1985)

$$T_s = K_2 / (\ln (K_1 / L[\lambda] + 1)) \tag{8}$$

where K_1 is the first constant (60.776 mw cm^{-2} sr^{-1} m^{-1}), K_2 is the second constant (1260.56 °K), and L[λ] is the spectral radiance reaching the sensor (mw cm^{-2} sr^{-1} m^{-1}).

RESULTS AND DISCUSSION

The components of the radiation balance were calculated from Landsat TM data acquired under clear sky conditions. Field measurements of these components were acquired over dry and wet meadow test sites on Niwot Ridge. Results of the calculation of instantaneous values for Rn and its components, at the time of Landsat overflight (June 29, 1984 - 10:11:57 local time), are given in Table 1. All fluxes (except albedo) are expressed in Wm^{-2}.

Table 1

Net radiation components of dry and wet meadow sites on Niwot Ridge as computed from the model

	Dry Meadow	Wet Meadow
K↓	912.88	943.73
α	0.19	0.15
L↓	240.64	240.52
L↑	415.72	396.60
Rn	564.35	646.06

All computed fluxes are in error of less than 5% from field measurements obtained over the same test sites. These instantaneous values of the components of net radiation may be useful for estimating the spatial distribution of ET within the alpine tundra zone, but daily totals are more appropriate for climate related studies. Since remotely sensed measurements of Rn yield instantaneous data, it is necessary to devise ways to infer values on a daily basis. Preliminary experimentations indicate that it may be possible to model daily variations in surface temperature at the regional scale given that both measurements of surface albedo (derived from Landsat TM) and solar irradiance (derived from a two-stream radiative transfer scheme) are available. This will be more fully investigated in the future.

FUTURE IMPROVEMENTS

Although results of this study show that reasonable estimates of the components of Rn can be obtained using the proposed model, problems remain in the determination of daily totals (e.g. surface temperature). An experiment therefore needs to be carried in order to model daily variations in surface temperature (over selected cover types) using Landsat-5 TM thermal Band 6 coupled with the radiative transfer model presented herein. Such experiment may reveal that methods proposed for local scale estimates (ex. Isard and Belding, 1988) are also useful for verifying regional scale estimates of ET, or calibrating models that use satellite data as inputs. Only through proper parameterization of the significant inputs can one hope to obtain reasonable estimates of ET from remotely sensed imagery in mountainous terrain.

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REFERENCES

Abdellaoui, A., F. Becker and E. Olory-Hechinger, 1986. Use of Meteosat for mapping thermal inertia and evapotranspiration over a limited region in Mali. Journal of Climatology and Applied Meteorology, 25, 1489-1506.

Becker, F., P. Camillo and B. Choudhury, 1987. Review of ET estimation by means of satellite data. Proceedings of the ISLSCP Workshop on Algorithms, Pasadena, CA, 5-9 June, 39pp.

Carlson, T.N., J.K. Dodd, S.G. Benjamin et J.N. Cooper, 1981. Satellite estimation of the surface energy balance, moisture availability and thermal inertia. Journal of Applied Meteorology, 20, 67-87.

Duguay, C.R. and E.F. LeDrew, 1992. Estimating surface reflectance and albedo from Landsat-5 Thematic Mapper over rugged terrain. Photogrammetric Engineering and Remote Sensing, 58, 551-558.

Idso, S.B., T.J. Schmugge, R.D. Jackson and R.J. Reginato, 1975. The utility of surface temperature measurements for the remote sensing of soil water content. Journal of Geophysical Research, 80, 3044-3049.

Isard, S.A., 1986. Factors influencing soil moisture and plant community distribution on Niwot Ridge, Front Range, Colorado, U.S.A. Arctic and Alpine Research, 18, 83-96.

Isard, S.A. and M.J. Belding, 1988. Evapotranspiration from the alpine tundra of Colorado. Arctic and Alpine Research, 20.

Penman, H.L., 1956. Evaporation: An introductory survey. Netherlands Journal of Agricultural Science, 4, 8-29.

Schott, J.R. and W.J. Volchok, 1985. Thematic Mapper thermal infrared calibration. Photogrammetric Engineering and Remote Sensing, 51, 1351-1357.

Séguin, B. and B. Itier, 1983. Using midday surface temperature to estimate daily evaporation from satellite thermal IR data. International Journal of Remote Sensing, 4, 371-383.

Taconet, O., R. Bernard and D. Vidal-Madjar, 1986. Evapotranspiration over an agricultural region using a surface flux/temperature based on NOAA-AVHRR data. Journal of Climate and Applied Meteorology, 25, 284-307.

Zdunkowski, W.G, W.-G. Panhans, R.M. Welch and G.J. Korb, 1982. A radiation scheme for circulation and climate models. Beitr. Phys. Atmosph., 55, 215-238.