QUANTIFYING THE SPATIAL DISTRIBUTION OF EVAPOTRANSPIRATION WITH SATELLITE DATA*

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ABSTRACT

Evapotranspiration (ET) is the sum of water vapor fluxes from transpiration of leaves and evaporation from the soil and from wet leaves. It is not only closely related to plant growth and carbon uptake but also an important hydrological component affecting runoff, ground water and atmospheric circulation. ET magnitude and variability are of key concern in climate change research. Remote sensing techniques offer the possibility of quantifying the spatial and temporal variations of ET. By using satellite data as inputs, ET over the entire Canada's landmass was calculated at 1 km resolution with a computer model, the Boreal Ecosystems Productivity Simulator (BEPS) (Liu et al., 1997). The satellite data, which include land cover (annually) and leaf area index (10-day intervals), were derived from the Advanced Very High Resolution Radiometer (AVHRR) on board of NOAA satellites. The ancillary data were meteorological data (daily) and soil texture. The Penman-Monteith method was used but theoretically modified to consider: (1) non-linear response of the conductance to diurnal variation of weather conditions, and (2) the effects of canopy architecture on canopy conductance. The results were validated using measurements from Saskatchewan and Manitoba made as part of BOReal Ecosystem-Atmosphere Study (BOREAS).

1.0 INTRODUCTION

By comparing different methods of estimating ET, Jensen et al. (1990) found that the Penman-Monteith (Monteith, 1965) equation provides the most accurate values. However, the global and regional use of the Penman-Monteith's formula is often hampered by the need for

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vegetation data, such as leaf area index (LAI), and hourly climate data, including net radiation, temperature, humidity, and wind speed. Because of this, other methods requiring less input data, mostly only air temperature, have been more widely used for global and regional calculations of ET (Willmott et al., 1985; Potter et al., 1993). Recently, remote sensing data, either LAI or climate parameters, have been employed to estimate ET using the process-based Penman-Monteith's equation for large area applications (Choudhury, 1997; Running et al., 1989).

In this study, ET is calculated at daily steps with the Penman-Monteith equation. A numerical scheme is developed to parameterize a key variable in the equation, canopy conductance (or its inverse, canopy resistance), for the calculation at such time step. The scheme is tested with field measurements in a large-scale international experiment: BOREAS. With a computer simulation system, a preliminary Canada-wide ET map in 1994 is produced.

2.0 METHOD

2.1 CALCULATION OF EVAPOTRANSPIRATION

Evapotranspiration is the sum of the transpiration from leaves and the evaporation from soil and wet plants. Transpiration generally contributes the largest portion of ET for a vegetated land.

Daily total ET is calculated according to the Penman-Monteith equation:

$$ET = \left[\left(\frac{\Delta R_{ni} + \rho c_p VPD / r_a}{\Delta + \gamma(1 + r_c / r_a)} \right) / (LE * 1000) \right] * Daylength$$

where ET is in m^3 day^{-1}; R_{ni} is daily mean net absorbed radiation in W m^{-2}; Δ is the rate of change of saturation vapor pressure with temperature in mbar $^oC^{-1}$; ρ is the density of air (=1.225 kg m^{-3} at 15 ºC); c_p is the specific heat of air at constant temperature (=1010 J kg^{-1} $^oC^{-1}$); VPD is vapor pressure deficit in mbar; r_a is aerodynamic resistance (fixed at 5.0 s m^{-1} in this study); γ is psychometric constant (=0.646+0.0006*T_a, where T_a is air temperature); LE is the latent heat of vaporization of water which is dependent on temperature (=(2.501-0.0024*T_a)*10^6) in J kg^{-1}; *Daylength* is day length in s; and r_c is daily mean canopy resistance to water vapor for transpiration calculation (see below for more detail). To calculate evaporation from the soil, r_c is replaced with soil resistance, which is a function of soil moisture calculated with the "bucket method" (Running and Coughlan, 1988). Evaporation from plants is estimated from the amount of rainfall interception according to meteorological conditions and LAI.

2.2 DAILY INTEGRATION OF CANOPY CONDUCTANCE ($CC_{m,d}$ =1/r_c):

Starting from stomatal conductance, daily mean canopy conductance is obtained from the following integration:

Stomatal conductance (SC):

Stomatal conductance at a given time is determined as follows:

$$SC = \begin{cases} C_1 PAR & PAR < PAR_c \\ C_2 & PAR \geq PAR_c \end{cases}$$

$$PAR = PAR_o exp(-KL/cos\theta)$$

where PAR is photosynthetically active radiation; PAR_c is a threshold, above which, stomatal conductance becomes saturated. C_1 and C_2 are species-dependent coefficients. PAR_0 is the PAR incident on the top of the canopy; θ is the solar zenith angle; and L represents LAI. K is equal to Ω G(θ), where Ω is the clumping index and G(θ) is the projection of unit leaf area, being equal to 0.5 (Chen, 1996).

Canopy conductance at a given time (CC):

To consider the effects of canopy structure, canopy conductance at a given time is estimated by integrating stomatal conductance vertically down along plant canopy:

$$CC = \int_0^L SC\, dL = \int_0^{L_c} C_2\, dL + \int_{L_c}^{L} C_1\, PAR\, dL = C_2 L_c + \frac{C_1}{K} PAR_0 \cos\theta(\exp(-KL_c/\cos\theta) - \exp(-KL/\cos\theta)),$$

where L_c is a threshold LAI, below which stomatal conductance is constant (saturated).

Daily mean canopy conductance ($CC_{m,d}$):

Finally, in considering non-linear response of the conductance to diurnal variation of weather conditions, a daily integration of canopy conductance at a given time is made, i. e. :

$$CC_{m,d} = \frac{1}{\frac{\pi}{2} - \theta_n} \int_{\theta_n}^{\pi/2} (C_2 L_c + \frac{C_1}{K} PAR_0 \cos\theta(\exp(-KL_c/\cos\theta) - \exp(-KL/\cos\theta)))d\theta$$

where θ_n is the solar zenith angle at noon.

An analytical solution to this integral is found under some assumptions and is used as an input to the Penman-Monteith's equation.

2.3 VALIDATION WITH BOREAS EXPERIMENT DATA

BOREAS took place in central Canada between 1994 and 1996. Two sites with tower flux measurements are selected for validation: a mature aspen site (53.629 ºN, 106.20 ºW), and a mature black spruce site (55.879 ºN, 98.48 ºW). For both sites, eddy covariance measurements were made above the canopy. The measurements in 1994 and 1996 were collected for the aspen site and spruce site, respectively. The originally measured half-hourly water vapor flux data were summed to obtain the daily totals. Radiation, temperature, and vapor pressure deficit measured from the towers were collected and processed. Missing data were supplemented with the meteorological data generated by NCAR (National Center for Atmospheric Research, USA).

2.4 CALCULATION OF REGIONAL EVAPOTRANSPIRATION

Regional evapotranspiration was calculated with a process model, the Boreal Ecosystems Productivity Simulator (BEPS). BEPS is built on the basis of the Forest BioGeochemical Cycles (Forest-BGC) model (Running and Coughlan, 1988) after several major modifications to adapt it to the boreal environment (Liu et al., 1997). The model requires the input of vegetation data (leaf area index, land cover), meteorological data (radiation, temperature, humidity and precipitation), and soil data (available water holding capacity). These data were collected at various temporal and spatial resolutions (Table 1) and preprocessed into a common format prior to simulation. The vegetation data were derived from AVHRR imagery. Spatial meteorological data were obtained with a new scheme (Liu et al., 1997), by using gridded meteorological data generated by numerical weather forecast models. Soil polygon data were mosaicked, georeferenced and rasterized in a geographic information system (ARC/INFO). BEPS is run at daily steps in a spatially explicit mode for every 1 km x 1 km pixel over the entire country.

3.0 RESULTS AND DISCUSSION

3.1 VALIDATION

Validation results based on the BOREAS data are shown in Figure 1. For this validation, the meteorological data measured at the site were used. In general, the estimates are close to the measured values. A better comparison between the modeled and measured ET is found with the aspen stand ($r^2 = 0.84$) than with the spruce stand ($r^2 = 0.61$). The highly clumped canopy in the spruce stand could cause some inaccuracies in the simple Penman-Monteith model and may be one of the reasons for the low r^2. Lack of understory data may be another reason. Deciduous forest generally transpires more than coniferous forest, even if the LAI of deciduous forest is the same or lower than that of the coniferous forest.

3.2 EVAPOTRANSPIRATION IN CANADA, 1994

Figure 2 shows a preliminary ET map over Canadian landmass for the year 1994 in which the daily estimates were summed for each pixel. The distribution of ET reflects the combined effect of vegetation, weather and soil. High ET is evident in a band across the boreal forest, especially in the area with deciduous and mixed forest. Another region with high ET is the forested area of Vancouver Island. The low values near water bodies (lakes) are caused by frequent cloud cover (low available energy) and high atmospheric humidity (low driving force). The low ET above 52 ºN along the west coast is mainly due to low LAI, although precipitation there was high.

3.3 FUTURE WORK

High quality of climate and soil data are essential for an accurate estimation of ET. Further studies can be oriented in the following directions: (1) deriving radiation and temperature distribution from satellites; (2) estimating soil moisture from space; (3) taking more climate variables, such as wind speed, into consideration; (4) improving the temporal interval and spatial resolutions with reliable quality; (5) linking BEPS with a climate circulation model; and (6) validation and refinement of ET at high resolutions or at landscape levels.

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Table 1. Input data sources and formats

Parameter	Source	Agency[1]	Data Type	Grid System	Temporal Interval	Grid Sise
LAI	AVHRR[2]	CCRS	Raster	Pixel/Line	10 days	1 km
Land cover	AVHRR[2]	CCRS	Raster	Pixel/Line	Annual	1 km
AWC	SLC[3]	CLBRR	Vector		Long term	
Radiation Temperature Humidity Precipitation	The NMC Medium Range Forecast Model	NCAR	Raster	Gaussian	Daily	~0.9 degree (varied with lat./long)

[1]CCRS: Canada Centre for Remote Sensing, Natural Resources Canada.
CLBRR: Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada.
NCAR: National Center for Atmospheric Research, USA.
[2]Advanced Very High Resolution Radiometer.
[3]Soil Landscapes of Canada.

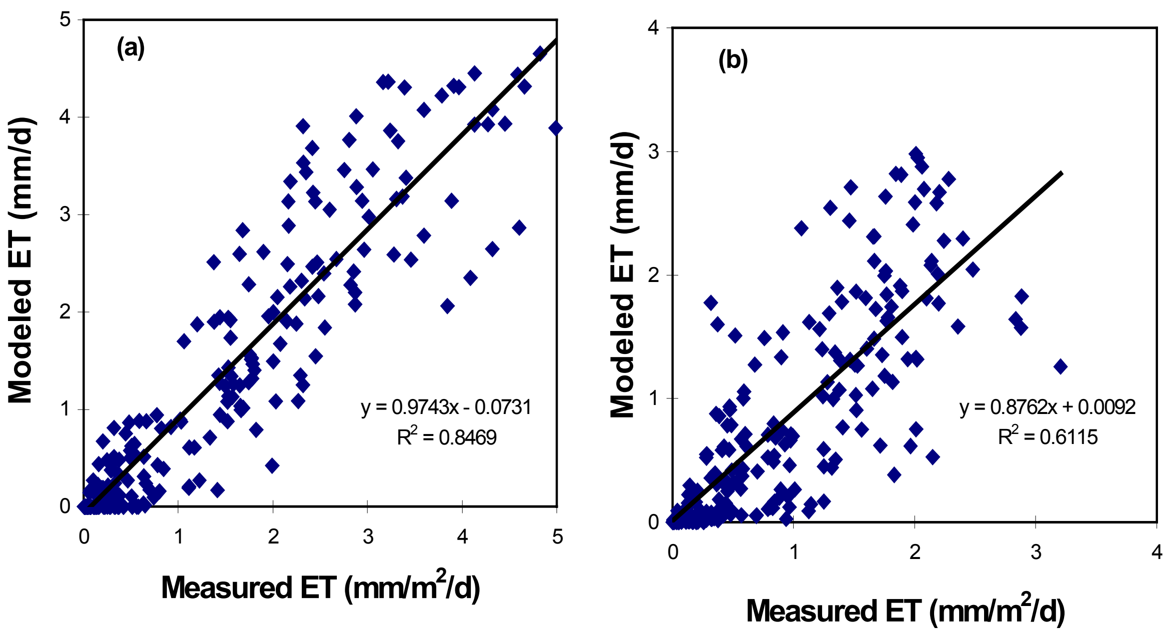

Fig. 1. Comparison of the measured ET with the modeled daily ET for a mature aspen stand (a), and a black spruce stand (b).

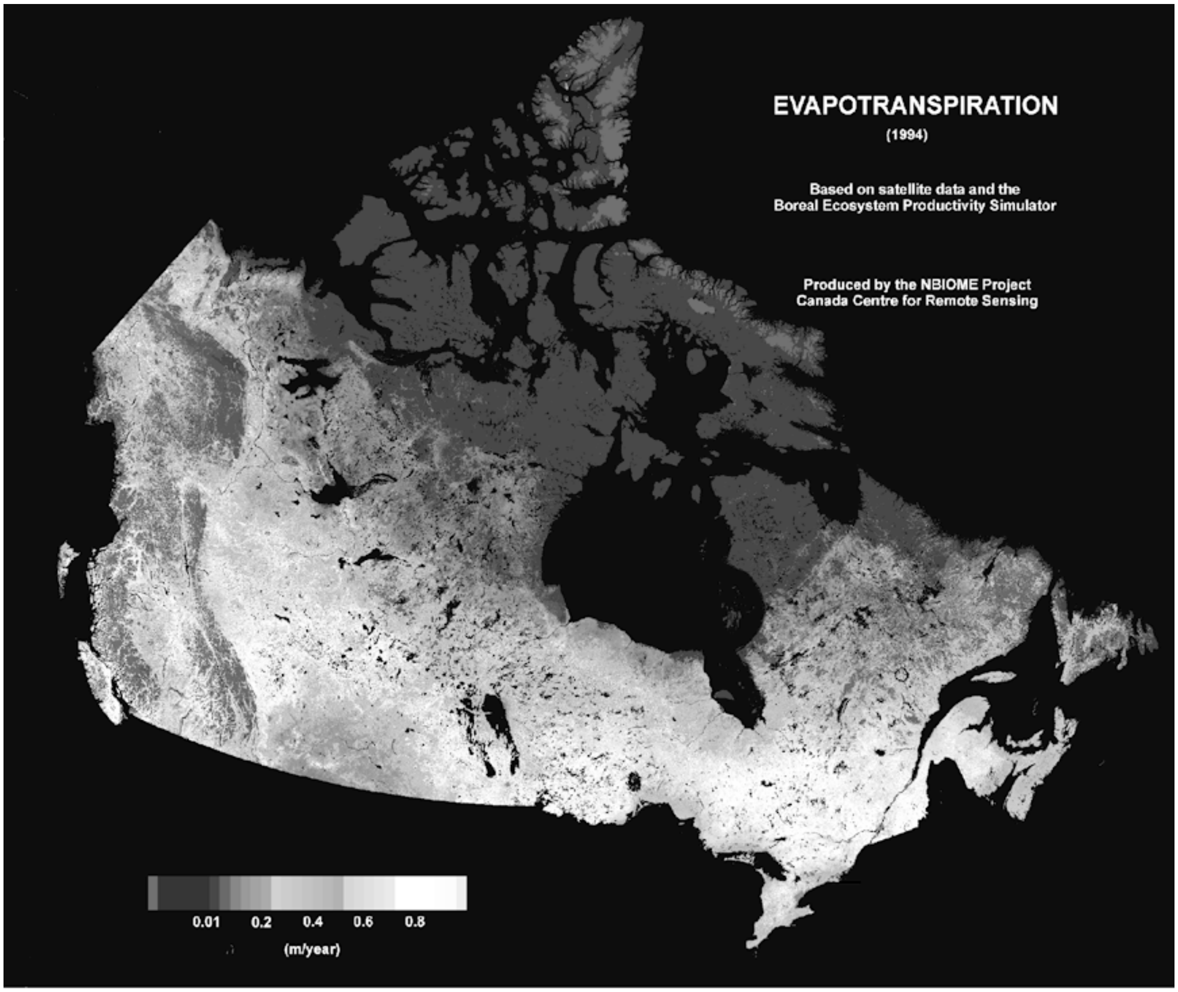

Figure 2. A preliminary ET map over Canada land mass for 1994.