

Direct estimation of stomatal resistance for meteorological applications

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Abstract. Stomatal Resistance (R_s) is one of the most important parameters in the meteorological models for weather or climate analysis and hydrological scenario estimations. The information for estimating R_s is sparse particularly in the tropics limiting the development of a detailed global terrestrial biosphere-atmosphere interaction analysis. One of the reasons for the scarcity of tropical data is the high cost of instrumentation. A hypothesis is presented to estimate R_s from plant-nutrient status in a field study using stomatal aperture observations to develop a simple, cost-effective technique for first-order estimations. Comparisons with observations from a tropical field experiment are encouraging and an approach is suggested using this method for initialization of numerical models using remote sensing techniques based on nitrogen, humidity, and temperature as sufficient parameters.

Introduction

Stomatal resistance (R_s) is a pivotal parameter for soil-vegetation-atmosphere transfer (SVAT) studies [Niyogi and Raman, 1997]. R_s quantifies the transpiration influencing the evapotranspirative or the latent heat flux (LHF). An error in estimating R_s propagates into LHF estimation, which due to energy-balance, propagates into the sensible heat flux (SHF) calculations [cf. Baldocchi, 1994]. This affects features at diverse scales such as boundary layer development [Alapaty et al., 1997a], local circulation [Pielke et al., 1997], cumulus formation [Hong et al., 1995], and even global precipitation and vegetation changes [Archer et al., 1995].

R_s is modeled based on either photosynthesis (A_n) calculations [cf. Niyogi and Raman, 1997] or by scaling a minimum stomatal resistance ($R_{s_{min}}$) [cf. Jarvis, 1976; Alapaty et al. 1997a; however also see Monteith, 1995]. The photosynthesis approach is apparently more mechanistic and correct but is iterative and computationally expensive. This makes the $R_{s_{min}}$ or the Jarvis-type approach more popular in the operational meteorological models. Also, within the uncertainties for the input parameters at a regional scale

[Alapaty et al., 1997b; Niyogi et al., 1997], the two approaches are hypothesized to provide similar R_s outcome [Niyogi and Raman, 1997]. However, to test such a hypothesis and to analyze the regional or global hydrological or energy budgets and ecosystem dynamics, one requires data under different geographical setups with regionally representative values for R_s . To realize this objective, rigorous measurements at the "grass root" level with high spatial and temporal resolution are necessary particularly in the tropics and the developing countries [cf. Korner, 1994; Schulze et al., 1994].

R_s measurements through porometry or gas-exchange techniques have high precision and accuracy and hence a justifiable high cost. However, for a typical tropical research station in a developing country, the instrument cost could be prohibitive. This is one of the practical reasons for the paucity of good and continuous data for evapotranspiration and ecophysiological interactions for such regions. It is for this purpose that a cost-effective approach that would give approximate R_s values is required. The methodology described here is directed towards this objective.

Objective

In the Jarvis-type approach, $R_{s_{min}}$ has to be assigned *a priori* in the models based on available literature [Alapaty et al., 1997a] or back-interpolation studies [Dorman and Sellers, 1989] and has a large uncertainty [Alapaty et al., 1997b]. $R_{s_{min}}$ can be, however, a link for the physiological and phenological composition of the vegetation when the approach is towards a dynamic analysis [Henderson-Sellers, 1993]. Recently, Schulze et al. [1994; henceforth S94], reviewed the available literature and showed a correlation between the plant nutrient status [leaf nitrogen content: N] and maximum stomatal conductance ($g_{s_{max}}$: inverse of $R_{s_{min}}$) represented as:

$$g_{s_{max}} \text{ (mm. s}^{-1}\text{)} = 0.3012 N \text{ (mg.g}^{-1}\text{)} \quad (1)$$

The S94 result is exciting, as it forms a basis of including a mechanistic, albeit correlational, feature for determining $R_{s_{min}}$ in the Jarvis-type analysis for observations or model analysis. Within this perspective, our emphasis is on the following issues:

(i) How does the nutrient-based N - $R_{s_{min}}$ relation of S94 perform under typical tropical field conditions?

(ii) Can this technique be used to develop an inexpensive method for a routine first-order approximation of stomatal resistance particularly for tropics? Can the technique be scaled for different spatial resolutions?

(iii) What are the "minimum and sufficient" parameters for regional evapotranspiration and meteorological analysis?

These and related aspects are discussed in this paper based on the field observations made during the Vegetation and Energy Balance Experiment in the tropics (VEBEX) [Raman *et al.*, 1997].

Approach and Hypothesis Testing

The data used here is from VEBEX conducted from July 1995 to January 1996 over a tropical station in the University of Agricultural Sciences at Bangalore, India (12° 59' N, 77° 40' E). The crop grown was *Dolichous-biflorus* (horse gram). Table 1 shows the LAI and vegetal cover fraction over the study period along with the changes in the plant shoot-root length and leaf nitrogen content during this period and the R_s related information. R_s was measured using a steady-state porometer (Delta-T AP3) typically at noon, while leaf nitrogen content was estimated in the laboratory using titration technique. The range of measured R_s is 20.4 to 41.3 s.m⁻¹ (averaged at 28.3 s.m⁻¹) with the lower values at the later stages of the plant growth. Typically (though not always, cf. Collatz *et al.*, 1991) mid-afternoon stomatal resistances are the lowest [cf. Kim and Verma, 1991] for a wide range of landscapes. Thus the afternoon measurements reported here, can be taken as an indication of the possible R_{smin} for the foliage (a quantity which cannot be measured *per se*). Comparing this with the S94 relation (Eq. 1), the R_{smin} range suggested is 10.51 - 59.29 s.m⁻¹ (average: 20.16 s.m⁻¹). The two are fairly similar thus supporting the applicability of the concept in a tropical setup. A known trend [Korner, 1994] of the reduced resistances for the growing crop is also captured in the observations and S94 estimates. This suggests that there could be potential for using the S94 equation as a possible mechanistic descriptor for the Jarvis-type analysis.

How can this relation be extended for a direct, cost-effective approximation of stomatal resistance? The methodology devised for this, assumes the following premise: (i) stomatal conductance (g_s) is entirely governed by the stomatal aperture that is, opening or closing of the stomata, [cf. Kappen *et al.*, 1994]; (ii) the maximum stomatal conductance (g_{smax}) or the least resistance corresponds to a situation when all the stomates are open and free to transpire (which is consistent with the definition), (iii) the ratio of the number of stomates open to the total number present can scale the minimum resistance to the actual resistance (which is the hypothesis to

be tested), and (iv) the stomatal response being a function of the nutrient status will depend on the foliage age (young, mature, or old) [cf. Korner, 1994]. Note that assumption three (using a ratio rather than functional form) is considered for linearity in scaling and is not governed by any elegant analysis (also see Kim and Verma, 1991). With these assumptions, the conductance (g_s ; inverse of R_s) for the entire plant (or region as described ahead), can be estimated as:

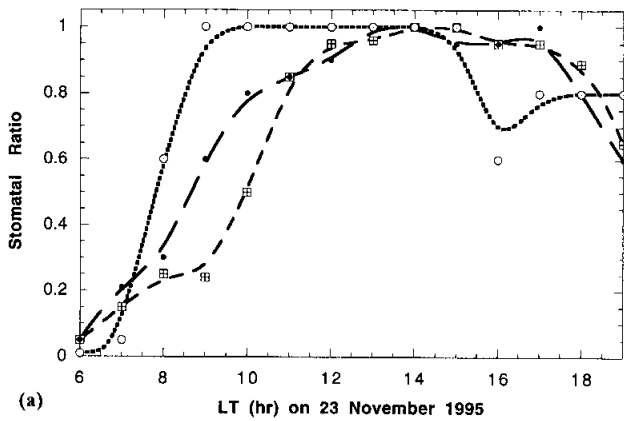
$$g_s = \sum_{\text{groups}} g_{smax} \frac{(\text{open_stomates})}{(\text{total_stomates})} \times \text{fraction of the foliage for that age group} \quad (2)$$

R_s is then taken as inverse of g_s . Note that, g_s cannot be replaced by R_s by replacing g_{smax} to R_{smin} in Eq. (2) due to linearity constraints.

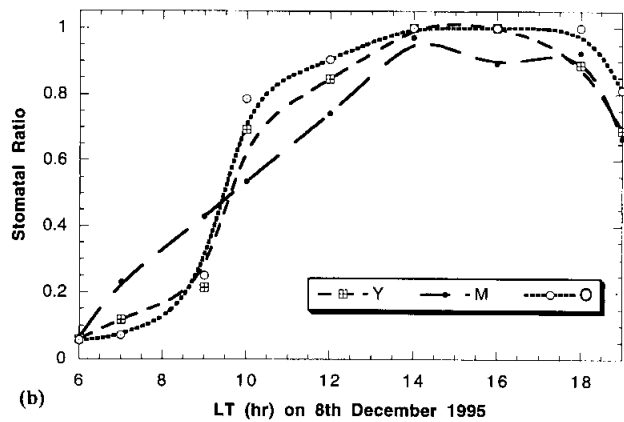
The proposed approach is validated using VEBEX observations. During VEBEX, as shown in Table 1, N was determined for different plant stages (the crop was sowed on August 14th, 1995). Thus g_{smax} (reciprocal of R_{smin}) was known. Additionally, the "stomatal-ratio" (SR : ratio of open to the total stomates) was measured in the field by taking a section of a leaf sample and viewing it microscopically. The number of stomates present in the view and the number open were recorded. The third plactecron leaves were considered 'young'; tenth to twelfth as 'mature' and bottom leaves 'old' (the 'old' leaves were often mutilated or turning pale). SR is assumed to be an indicator for the transpiration potential under ambient conditions. The temporal variation of the SR as obtained for three days (each under different vegetation stage; see Table 1) during VEBEX is shown in Fig. 1 a-c. The variation is qualitatively similar to various observations of the transpiration potential available in the literature [cf. Korner, 1994]. The ratio was low in the morning (around 6 hrs LT) and peaked around noon persisting even after sunset showing a hysteresis in the response which can be related to the surface temperature. This feature was also found in the observations of Kappen *et al.* [1994]. This hysteresis is apparently more pronounced for the older leaves in the data. Additionally, with crop growth, the early morning SR increased from a near zero in November to about 0.17 in December. Thus, the stomates in mature leaves, in general, appear to be in equilibrium with the ambient environment. An estimate was also made of the fraction of young, mature, and old vegetation (Table 1), in addition to the vegetal cover and LAI for the field for the study period. Thus, with all the information required for Eq. (2) available, R_s was estimated. The temporal variation of the estimated R_s is shown in Fig. 2. Unfortunately, for this phase of VEBEX, detailed porometric observations were not available. However, the estimated R_s

Table 1. Estimated R_{smin} and Observed N and other Vegetation Parameters during VEBEX

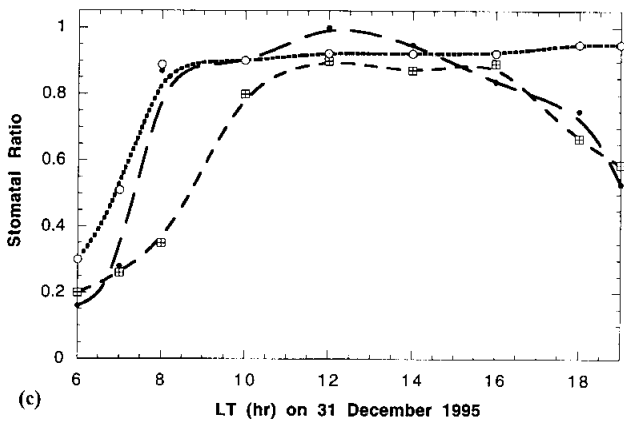
Date in 1996	LAI	Vegetal Cover	% Vegetation			N (mg/g)			R_{smin} (s/m)			R_{sobs} (s/m)
			Y	M	O	Y	M	O	Y	M	O	
Oct. 13	0.21	0.25	0.4	0.55	0.05	56	78	73	24.41	13.77	36.09	41.3
Nov. 23	0.54	0.85	0.25	0.65	0.1	89	164	122	22.59	12.03	27.21	29.1
Dec. 8	0.61	0.97	0.15	0.7	0.15	116	196	163	19.19	10.15	24.41	22.5
Dec. 31	0.46	0.85	0.05	0.75	0.2	179	316	144	18.55	10.51	23.06	20.4



(a)



(b)



(c)

Figure 1a-c. Observed 'Stomatal Ratio' (SR) for the three observation days. 'Y' refers to young, 'M' refers to mature, and 'O' to old leaves.

trend is consistent with previous sophisticated observations [cf. Korner, 1994]. Thus, we suggest, within the observation uncertainties, there is a potential of its application under field conditions in the absence of porometry measurements.

Advantages, Limitations, and Applications

The approach presented has certain caveats: (i) SR is based on human interpretation and hence prone to error; (ii) While taking a sample, the leaf is actually given a stimulus which can alias the stomatal ambient status with the induced stimulus in some cases; (iii) there could be non-homogeneous distribution of the stomates on the leaves of certain plants [cf.

Beyschlag and Pfanz, 1990]; and (iv) the S94 relation has an inherent uncertainty. However these uncertainties can be reduced by estimating the stomatal ratio on different leaves. These uncertainties might not simply add-up and could even cancel out as demonstrated by Niyogi et al. [1997] and can be tolerated for first-order estimates. The study also suggests that the plant nutrient status predicted by the ecological component of the model can be efficiently linked with the physiological and evapotranspiration modules for the coupled "earth-system" approach [cf. Foley et al., 1997]. Another possible advantage would be the development of a larger plant nutrient database in tropics and sub-tropics where sophisticated instrumentation is not available. It is again important to note that this technique is *not* a substitute for porometry and may be used when porometry or other more rigorous techniques are not available.

How can this approach be used for a regional analysis? Attempts are underway for adopting better indices than the Normalized Differential Vegetation Index [C. Wessman, personal communication, 1996] in remote sensing of the biophysical processes [also see, Hobbs and Mooney, 1990]. If the regional vegetation is characterized on the basis of foliage age and nutrient status, it should be possible to have a reasonable estimate of the stomatal or evapotranspirative activity. The same methodology applied for the canopy-scaling can be adopted to a regional scale except that SR will have to be parameterized. One possible way could be to scale it as a function of relative humidity (RH) and temperature (T). The choice of relative humidity as a factor is prompted by two aspects: it can be estimated from remote sensing, and it forms a reasonable, albeit combined, signature of regional water-stress and humidity [cf. Mahfouf, 1991; but also see Aphalo and Jarvis, 1991]. Thus Eq. (2) can be reformulated as:

$$R_s = \sum f_{age} \cdot 0.3012 N \cdot f(RH, T) \tag{3}$$

where, f_{age} is the fraction of the foliage by age. Past studies by [cf. Wessman et al., 1988], have established a possibility of regional N related measurements using remote sensing. Also, SVAT modeling has reached a stage where, parameterizations are reasonably sophisticated but the practical difficulty is in providing the input conditions to these models at a regional scale [cf. Pielke et al., 1997]. Hence, it will be pertinent to test this approach for biophysical routine initializations. Eq. (3) also suggests, for meteorological modeling at a regional scale, N, RH, and T can be the "minimum and sufficient"

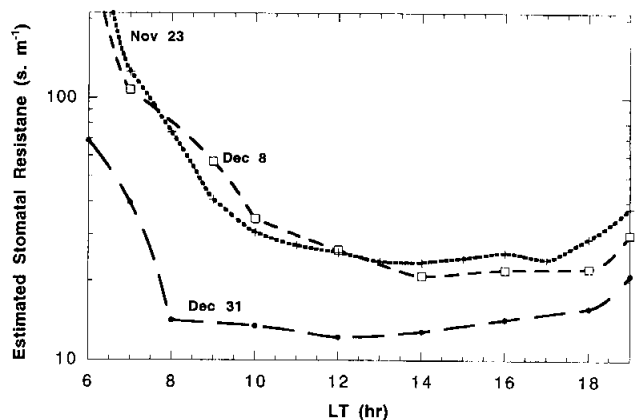


Figure 2. Estimated stomatal resistance (y-axis, log-scale) for the three days during VEBEX.

parameters for transpiration estimates. This approach appears promising with significant practical applicability in the initialization of the biophysics in the land surface processes.

Conclusions

A simple hypothesis for estimating stomatal resistance in the absence of porometry is presented. The hypothesis relies on the plant nutrient status measurements and direct observations stomates using microscope on field and thus attempts to mimic the mechanistic response in a simplified manner. This technique has performed reasonably well in the present study though further testing under different climatic conditions and for different plants is required. In the absence of porometry, this technique can be of use particularly in tropics and in locations where economy in measurements is a consideration to obtain more representative and regionally distributed information regarding evapotranspiration and plant nutrient status through better remote sensing techniques. Possibility of using this hypothesis for model initializations and regional analysis is suggested using N , RH , and T as the signatures for terrestrial ecosystem in SVAT analysis.

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