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Simulating canopy stomatal conductance of winter wheat and its distribution using remote sensing information

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Abstract: The canopy stomatal movement, a plant physiological process, generally occurs within leaves but its influence on exchange of CO_2, water vapor, and sensible heat fluxes between atmosphere and terrestrial ecosystem. Many studies have documented that the interaction between leaf photosynthesis and canopy stomatal conductance is obvious. Thus, information on stomatal conductance is valuable in climate and ecosystem models. In current study, a newly developed model was adopted to calculate canopy stomatal conductance of winter wheat in Huang-Huai-Hai (H-H-H) Plain of China (31.5 - 42.7°N, 110.0 - 123.0°E). The remote sensing information from NOAA-AVHRR and meteorological observed data were used to estimate regional scale stomatal conductance distribution. Canopy stomatal conductance distribution pattern of winter wheat on March 18, 1997 was also presented. The developed canopy stomatal conductance model might be used to estimate canopy stomatal conductance in land surface schemes and seems can be acted as a boundary condition in regional climatic model runs.

Keywords: remote sensing information; winter wheat; stomatal conductance; H-H-H(Huang-Huai-Hai)Plain

Introduction

The climate change is significantly affecting human living environments in global, regional, and local scales. In terms of the regional scale, one of the most promising approaches for simulation of regional climate change is the development of regional climate model (RCM). It is well recognized that land surface is an active interface of interaction among the atmosphere, vegetation, and soil; and each system is linked together through physical, chemical, and biological processes. Thus, to develop the land surface process model is necessary in RCM. Many scientists also addressed that exchanges of energy, momentum, water, heat, and carbon between the land surface and the atmosphere must be expressed realistically and accurately in the next generation models of global change (Sellers, 1997).

Recent studies have shown that the canopy stomatal movement, a plant physiological process, occurs within leaves but its influence on fluxes of CO_2, water vapour, and sensible heat can be extended to canopy, regional, and global scales (Collatz, 1992; Dickinson, 1995; Sellers, 1996). The information on canopy stomatal conductance is valuable in climate, biology, hydro-ecology, agriculture, and ecosystem models. Therefore, schemes for estimating canopy stomatal conductance are essential.

Many pervious investigators have demonstrated that the NOAA-AVHRR satellite data provide us a powerful means, which we can monitor the seasonal and interannual dynamics of the global vegetation (Nemani, 1996) and can derive many kinds of landsurface parameters, i.e. surface temperature, albedo, surface roughness length, soil moisture, leaf area index, vegetation height and so on. Actually, the remote sensing of stomatal conductance also performed during last two decades. Sellers (Sellers, 1987) reported that the ratio of near infrared to read reflectance of a vegetation canopy is near-linear function of its maximum stomatal conductance. Verma *et al*. (Verma, 1993) tested the hypothesis (Sellers, 1987) that the simple ratio vegetation index (SR) should be near-linearly related to the derivatives of the unstressed canopy stomatal photosynthesis. Hope (Hope, 1988) estimated the canopy stomatal resistance (the reciprocal of stomatal conductance) using combined remotely sensed spectral reflectance and thermal observations. Sellers *et al*. (Sellers, 1992b; 1996) coupled the semiempirical leaf physiology model of Collatz *et al*. (Collatz, 1991) that explicitly linked stomatal function and leaf assimilation to a canopy radiative transfer model. In this coupled model, the input parameter derived from satellite data can be used to estimate canopy stomatal conductance spatial distribution. Myneni *et al*. (Myneni, 1992) used one-and three-dimensional radiative transfer models to derive simple algorithms for remote sensing of canopy conductance. Zhang (Zhang, 1996) also studied remote sensing of canopy stomatal resistance using crop water deficit index (CWDI) as an input parameter. However, until now, there is seldom studies have been undertaken to estimate stomatal conductance and its spatial distribution in China area using remote sensing data.

In current study, we adopted an algorithm to calculate stomatal conductance of winter wheat in Huang-Huai-Hai (H-H-H) Plain of China (Liu, 1992). The parameters of estimating canopy stomatal conductance have been derived from AVHRR data, and also obtained from surface observation data. The date selected for the analysis was March 18, 1997 in present study, while winter wheat was in its growing period.

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1 Methods

1.1 The influencing factors of canopy stomatal conductance

The role of physiological feedback in land-air exchanges is determined by the behavior of the canopy stomatal conductance (G_s). Water is taken up from the soil by plant roots and released into the atmosphere through tiny pore in leaf surface called stomata. CO_2 is drawn from the atmosphere into leaf interiors for photosynthesis through these same stomata process. It is believed that under normal conditions, the stomata are controlled to maximize the role of carbon assimilation for a minimal loss of leaf water. However, there are some additional effects that are induced in a leaf in response to stress; these include a progressive canopy stomatal closure as the external air dries and a similar closure response as decreasing soil moisture. While the exact mechanisms involved in sensing stress and inducing canopy stomatal closure is incompletely understood, the responses are behaved sufficiently to allow the construction of robust semi-empirical models (Sellers, 1992a).

Recent years, many studies have been carried out on G_s estimating models. Generally, the canopy stomatal conductance is correlated with a number of factors, such as short-term changes in water of leaf, saturation vapor pressure deficit, solar flux, temperature, and ambient carbon. The canopy stomatal conductance is thus a function of environmental and physiological conditions. A model first proposed by Jarvis (Jarvis, 1976) has been used widely to describe G_s. Jarvis first derived a maximum of G_s(G_{smax}) and multiply G_{smax} by series of the stress factors including the effects of photosynthetically active radiation (*PAR*), air temperature, leaf water potential, and vapor pressure deficit, the values of the nondimensional factors on being between 0 and 1. Choudhury and Idso (Choudhury, 1985) presented a G_s algorithm, in which the considered adjustment factors only included canopy stomal water potential and solar influx. Lu (Lu, 1992) summarized his own and others researcher work on the canopy stomatal conductance function, and proposed that the G_s can be a function of the visible flux, the air saturation vapor pressure deficit, and the leaf water potential. Table 1 compares the above three models.

Table 1 Stomatal conductance functions by variable

Modeler	$f(R_n)$	$f(D_{vp})$	$f(\psi_L)$	$f(T)$
Jarvis (1976)	R_n	D_{vp}	ψ_L	T_a
Choudhury (1985)	*PAR*	*	ψ_L	*
Lu (1992)	R_n	D_{vp}	ψ_L	*

The symbols (*) indicates not included. $f(R_n)$ refers to parameters relating G_s to solar flux, R_n is the net radiation, *PAR* is the photosynthetically active radiation proportional to 0.47 Q (Q is incident solar flux). $f(D_{vp})$, $f(\psi_L)$ and $f(T)$ are the adjustment factors to account for the effects of vapor pressure deficit, leaf water potential, and temperature stresses. D_{vp}, $f\psi_L$, and T_a represent the vapor pressure deficit, leaf water potential, and air temperature at z_a (reference height), respectively

In present study, Lu's model will be adopted to estimate canopy stomatal conductance, and the satellite data and meteorological observation data will be used to obtain some parameters for the model runs.

1.2 The simulated model of stomatal conductance

In Lu's model, the leaf stomatal conductance, g_s (mm/s), is taken to be a function of incident visible flux density, the atmospheric vapor pressure deficit, and the leaf water deficit, and is assumed to be given by

$$g_s = f(R_n) \cdot f_D \cdot f\psi_L, \tag{1}$$

where, $f(R_n)$ (mm/s) takes into account the effect of net radiation to stomatal conductance, the adjustment factor f_D and $f\psi_L$ both being dimensionless and between 0 and 1, represent the influencing factor of air saturation vapor pressure deficit and leaf water potential to stomatal conductance, respectively. $f(R_n)$ can be set by Equation (2)

$$f(R_n) = 2.867 + 0.0277 R_n, \tag{2}$$

where, R_n is the surface net radiation (W/m^2).

Leaf stomatal conductance is linearly related to saturation vapor pressure deficit (D_{VP}) (hPa) is as follows

$$f_D = 1 - 0.0254 D_{VP}. \tag{3}$$

The response of the leaf stomatal conduction to leaf water potential is computed using the relationship presented by Fisher (Fisher, 1981)

$$f\psi_L = 1/[1 + (\psi_L/q)]^P, \tag{4}$$

where, ψ_L is the leaf water potential (hPa), q and p are empirical parameters ($q = -31529.0$, hPa^{-1}, $p = 4.85$). Consequently, the leaf stomatal conductance is written by

$$g_s = (a + bR_n)(1 - cD_{VP})/[1 + (\psi_L/q)^P)], \tag{5}$$

where, $a = 2.867$ mm/s, $b = 0.0277$ mms^{-1}W^{-1}m^2, $c = 0.0254$ hPa^{-1}, $q = -31529.0$ hPa^{-1}, $p = 4.85$.

Considering the total depth of canopy, the insolation in LAI depth can be defined by the following equation (Goudriaan, 1973)

$$R_{ni} = R_n \times e^{-K \cdot LAI}, \tag{6}$$

where, R_{ni} is interior net radiation (Wm^{-2}), K is the extinction coefficient, and LAI is the leaf area index (mm^{-2}). The canopy stomatal conductance, G_s in unit of mms^{-1}, derived by integrating Eq.(5) for total leaf area with help of Eq. (6), can be given as follows

$$G_s = \int_0^{LAI} g_s dLAI = \int_0^{LAI} (a + bR_{ni})(1 - cD_{VP})/[1 + (\psi_L/q)^P] dLAI$$
$$= [aLAI + b(1 - e^{-K \cdot LAI})R_n/K](1 - cD_{VP})/[1 + (\psi_L/q)^P]$$

$$= \int_0^{LAI} (a + bR_n \times e^{-K \cdot LAI})(1 - cD_{VP})/[1 + (\psi_L/q)^P]dLAI. \tag{7}$$

Eq.(7) is rewritten with use of parameters given in Eq. (5) as follows

$$G_s = [2.867LAI + 0.0277(1 - e^{-K \cdot LAI})R_n/K](1 - 0.0254D_{VP})/\{1 + [\psi_L/(-31529.0)]^{4.85}\}, \tag{8}$$

where, G_s is the canopy stomatal conductance (mms^{-1}); LAI is the leaf area index (m^2m^{-2}); K is the extinction coefficient; R_n is the net radiation (Wm^{-2}); D_{VP} is the saturated deficit of water vapor pressure (hPa); ψ_L is the leaf water potential (hPa).

Eq.(8) will be used to calculate G_s in this paper.

1.3 Data

1.3.1 NOAA-AVHRR data

A better way to obtain global distributions of Land Surface Parameters (LSPs) is to use satellite data. In the last two decades use of AVHRR (The Advanced Very High Resolution Radiometer) with about one-day temporal and about 1.1 km spatial resolution has been prominent. AVHRR on board NOAA satellite series is a four- or five-channel scanning radiometer capable of providing global daytime and nighttime information about ice, snow, vegetation, clouds and the sea surface temperature. These data are obtained on a daily basis primarily for use in weather analysis and forecasting. However, a variety of other applications are possible, two of the most attractive of which are estimation on the land surface parameters of land surface in climate model and monitoring of vegetation dynamics (Zhang, 1999). Hence, the remote sensing information also can be used to estimate canopy stomatal conductance.

We have used NOAA-AVHRR image for clear day of different growing seasons in the study area in 1997. The date selected for the analysis in this paper was March 18, 1997 when the date the winter wheat was in its growing period in H-H-H Plain and when the NOAA-AVHRR image was clear and no cloudy. In current study, I_{NDV} (the Index of Normalized Difference Vegetation) and surface albedo (α) were calculated using channels 1 and 2 of NOAA-AVHRR data; surface temperature was derived from channels 4 and 5 of NOAA-AVHRR data (see below).

1.3.2 Surface meteorological observation data

In this study, we collected 95 meteorological station data covering whole H-H-H Plain area. The observation data included air temperature at 2m height, insolation, air related humidity, and precipitation on March 18, 1997 in H-H-H Plain of China. The collected soil moisture data was middle ten days of March from more than 30 observation station covering the plain.

1.4 Study site

The study site is located in 31.5—42.7°N, 110.0—123.0°E. In this region, the main water body includes Huanghe River (Yellow River), Haihe River, and Huaihe River, accordingly named Huang-Huai-Hai Plain. The total area is 5.6×10^5 km^2 (Wang, 1996) in H-H-H Plain covering Beijing, Tianjin, and Hebei, Henan, Shandong, and partly Anhui and Jiangsu provinces, where is main crop production region in China, the planting area of winter wheat covers 44.3% of whole winter wheat planting area in China. In this region, the main vegetation type is winter wheat in plant growing season from February to June.

Climatically, H-H-H Plain lies in transition zone between humidity climate in South China and arid climate in Northwest China. Annual average temperature is 1.5—15℃, annual precipitation is from 450 mm in the north part to 1400 mm in the south part.

1.5 The parameters calculation of canopy stomatal conductance

The schemes of calculating the parameters in Equation (8) for winter wheat in H-H-H Plain on March 18, 1997 are described as follows.

(1) R_n (net radiation, Wm^{-2})

$$R_n = (1 - \alpha)Q + \varepsilon_q\sigma T_a^4 - \varepsilon_s\sigma T_s^4. \tag{9}$$

The first term of Eq.(9), Q, is the insolation (downward short wave flux; Wm^{-2}); α is the surface albedo, the relationship between α and AVHRR albedo of channel 1 (CH1) and Channel 2 (CH2) is given by the following algorithm (Tian, 1990)

$$\alpha = (0.0168\text{CH1} + 0.1012\text{CH2} + 16.83)/100. \tag{10}$$

The second term of Eq.(9), $\varepsilon_a\sigma T_a^4$, is the downward long wave flux (Wm^{-2}; Brusaert, 1975), where ε_a is the air emissivity, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}Wm^{-2}K^{-4}$), T_a is the air temperature (K) at z_a (z_a = 2m). After Brutsaert (Brutsaert, 1975), ε_a can be written

$$\varepsilon_a = 1.24[e(T_a)/T_a]^{1/7}, \tag{11}$$

where, $e(T_a)$ is the vapor pressure (hPa) at air temperature T_a (K). The third term of Eq.(9), $\varepsilon_s\alpha T_s^4$, is the upward surface long wave flux (Wm^{-2}), where ε_s is the surface emissivity, is taken as 0.98 (Zhang, 1996; Labed, 1991; Humes, 1994). T_s is the surface temperature (K), it is calculated by the following regression equation (Price, 1990)

$$T_s = T_4 + 3.33(T_4 - T_5), \tag{12}$$

where, T_4(K) and T_5(K) are the AVHRR brightness temperature in channel 4 (10.5—11.5 μm) and channel 5 (11.5—12.5 μm) respectively at the top of the atmosphere in the two infrared bands of NOAA-AVHRR. T_4(K) and T_5(K) can be computed from observed radiance of channel 4 and 5 of NOAA-AVHRR (Sullivan, 1995). The relationship between the radiance and brightness temperature is expressed by following equation (Sullivan, 1995):

$$I_i(T_i) = I_0 + a(T_i - T_0)^2, \quad (13)$$

where, $I_i(T_i)$ is the observed radiance at brightness temperature T_i in channel i. From Equation (13), the brightness temperature can be given by:

$$T_i = T_0 + [(I_i(T_i) - I_0)/a]^{1/2}, \quad (14)$$

where, I_0, α and T_0 are the parameters given by 8.00, 0.0061 and 173.55 for channel 4, and 7.86, 0.00630 and 161.70 for channel 5 (Sullivan, 1995).

(2) D_{VP} (the saturation of the vapor pressure deficit, hPa): D_{VP} can be computed by

$$D_{VP} = E(T_a) - e(T_a), \quad (15)$$

where, $E(T_a)$ is the saturated vapor pressure at air temperature T_a (K), $e(T_a)$ is the vapor pressure at air temperature T_a (K), after Chen and Jiang (Chen, 1989), $E(T_a)$ is expressed by

$$E(T_a) = 6.11 \times 10^{\frac{7.5(T_a - 273)}{T_a - 35.7}}, \quad (16)$$

$e(T_a)$ is expressed by the following Equation (17)

$$e(T_a) = E(T_a) \cdot RH, \quad (17)$$

where, RH is the relative humidity, which is obtained from meteorological observed data.

(3) ψ_L (leaf water potential, hPa)

ψ_L is calculated by the following function (Liu, 1997)

$$\psi_L = 0.1367(T_c - T_a) - 0.6554 D_{VP} - 0.3006, \quad (18)$$

where, T_c is the canopy temperature (K), T_a is the air temperature (K) and D_{VP} is saturated vapor pressure deficit (hPa). T_a can be obtained from meteorological station observed data. The calculation of T_c is written by the following Equation (19) (Kerr, 1991)

$$T_c = -2.44 + 3.6T_4 - 2.6T_5. \quad (19)$$

(4) K (the extinction coefficients)

K is affected by different crop development period, varying between 0.2 and 0.7. An empirical constant of 0.28 for winter wheat in the study area was used in March of winter wheat growing period (Yang, 1991).

(5) LAI (leaf area index, $m^2 m^{-2}$)

The leaf area index of winter wheat is written by (Zhang, 1996)

$$LAI = K^{-1} \cdot \ln(1 - f_c)^{-1}, \quad (20)$$

where, f_c is the crop canopy coverage, after Ottle and Vidal-Madjar (Ottle, 1994), the f_c is the modeled using the empirical expression

$$f_c = (I_{NDV} - I_{NDVmin})/(I_{NDVmax} - I_{DNVmin}), \quad (21)$$

where, I_{NDV} (the Index of Normalized Difference Vegetation) is calculated using

$$I_{NDV} = (CH2 - CH1)/(CH2 + CH1), \quad (22)$$

where CH1, CH2 are the reflectance in red wave lengths (0.62—0.68 μm) and in near-infrared (0.77—0.86 μm), respectively (Tucker, 1979). I_{NDVmax} and I_{NDVmin} are the maximum and minimum value of I_{NDV} in crop whole growing period, respectively (here I_{NDVmax} = 0.98 and I_{NDVmin} = 0.05).

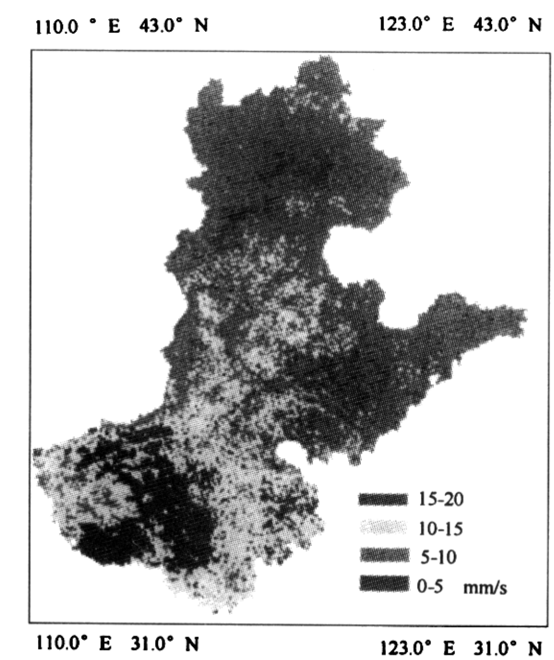

Fig.1 The stomatal conductance distribution of winter wheat in H-H-H Plain of China in March 18, 1997

2 Results and discussion

On the basis of the NOAA-AVHRR information and micro-meteorological data, the canopy stomatal conductance of winter wheat in H-H-H Plain of China was estimated. The canopy stomatal conductance distribution of winter wheat in H-H-H Plain of China on March 18, 1997 was presented. Fig. 1 shows the value of canopy stomatal conductance obviously decreases in the northward direction. The largest value in the south part of H-H-H Plain was ranged from 15—20 mm/s, while in the north part of H-H-H Plain of the mean value is ranged from 5—10 mm/s. The values are reasonable. The results reflected that the development of winter wheat in the south part of H-H-H Plain was better than that in the north part of H-H-H Plain in March 1997, and soil moisture in the south part was extremely higher than that in the north part.

3 Conclusions

Land process is a major but is currently treated as relatively weak ingredient of climate models (Dickinson, 1995). In this study we proposed a simple parameterization scheme of the canopy stomatal conductance. The G_s values might be used as a surface boundary condition of RCM. But the applicability of the surface canopy stomatal conductance scheme in this paper should be demonstrated in the forthcoming study. The Lu's model also might be used to estimate the net primary production (NPP) under crop water deficit condition in the future.

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