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Estimation of regional evapotranspiration over Northwest China using remote sensing

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Abstract: It is a very complicated problem to estimate evapotranspiration (ET) over a large area of land surface. In this paper, the evapotranspiration estimation models for dense vegetation and bare soil are presented, based on the information of parameters like vegetation cover-degree and surface albedo. Combined with vegetation cover-degree data, a model for regional evapotranspiration estimation over the heterogeneous landscape is derived. Through a case study using remote sensing data over Northwest China, the accuracy of the model for regional evapotranspiration estimation is checked. The result shows that the accuracy of the model is satisfactory. The features of evapotranspiration over Northwest China are also discussed with the application of the model.

Estimation of regional evapotranspiration over Northwest China using remote sensing CHEN Yun-hao, LI Xiao-bing, SHI Pei-jun (Institute of Resources Science, Beijing Normal University, Key Laboratory of Environmental Change and Natural Disaster, Ministry of Education of China, Beijing 100875, China) 1 Introduction The method for estimating evapotranspiration (ET) was first given by Dalton in 1802, and a number of models for ET estimation have been presented since then. Those models, from the experiential and semi-experiential models[1,2] and physical models[3,4] to the models in terms of the mechanism for energy and water fluxes in soil-vegetation-atmosphere transfer system such as SiB, have improved the precision of ET estimation. It is, however, difficult to calculate regional ET by using those models, because some parameters, such as solar radiation, wind speed and turbulent index are not fully considered or even ignored and because there has been a problem of transferring meteorological data from point scale to surface scale in those models. Over the last 20 years, scientific researches on regional ET with remote sensing data have been developed worldwide[5]. The energy exchanges of land surface are the main driving forces of climate change. If the information of energy balance is derived from remote sensing data, the estimation of ET can be obtained by using the equation of energy balance. According to this thought, Brown and Rosenberg (1973) gave the crops resistance-evapotranspiration model based on energy balance and crops resistance theory[5,6]. Later on, Sequin and Itier (1983) developed statistical models for daily evapotranspiration based on differentiation in temperatures of canopy and air, which were derived from the thermal infrared satellite data[7]. Xie (1991) introduced an improved calculation equation of aerodynamic resistance in terms of different meteorological conditions and neutral atmospheric stability[8]. Chen (1988) presented a concept of ¨excess resistance〃[9] based on vegetation-microclimate theory, which supplied calculation of aerodynamic resistance and improved estimation precision over the area covered with dense vegetation. In addition, Caselles (1988) and Carlson (1995) modified the parameters of the ET model to fit the features of certain study areas separately [10,11]. Regional ET includes two parts, i.e., transpiration and evaporation. The former is well correlated with the photosynthesis process of vegetation, and the latter is driven by solar radiation, temperature, precipitation and other meteorological factors. However, many differences between transpiration and evaporation are ignored in the above-mentioned models, with the result that those models are only workable for ET estimation over a uniform landscape or a small area. The purpose of this study is to seek an ET estimation model for a large area of natural land surface. In this paper, the ET estimation models for dense vegetation and bare soil are presented, based on the information of surface parameters. Combined with vegetation cover-degree data, a regional ET estimation model for heterogeneous landscape is given. With the application of the model, regional ET values of Northwest China are calculated and their characteristics are analyzed. 2 The model All kinds of the energy exchanges are driven by incoming surface net radiation, which can be represented as the following form: where LE is latent heat flux (L=2.49⊙106 Wm-2/mm), E is evapotranspiration (mm), Rn is the incoming net radiation, H is sensible heat flux and G is soil heat flux (W/m2). PH is the energy increment gained in plant photosynthesis and biomass increment which is normally ignored in calculation because of its relatively low value. Equation (1) is the basic equation to estimate ET. There are three potential surfaces of evapotranspiration in a region: bare surface, plant canopy surface and the mixed surface of bare soil and plant canopy. The parameters for dense vegetation and bare soil ET estimation are different because of different processes of water and energy transfers. ET models for bare soil and for vegetation are presented based on Equation (1) in this paper (parameters of models are given in the next section). The ET over a mixed area of bare soil and plant canopy can be calculated by the percentages of these two items, thus we get where Eg is the ET over complete vegetation cover, and E0 is the ET over the bare soil. The ¨f 〃, cover-degree of vegetation in a pixel, is the projected area of the vegetation per unit ground area, thus (1-f) is the projected area of the bare soil per unit ground area. Instantaneous regional ET at any time-of-day is given by Equation (2). There is a sinusoid relationship between daily ET and instantaneous ET, which is given by[8] where LEd is daily ET and LE is instantaneous ET at any time-of-day, and t is the data-collecting time of satellite pass by. NE is the daily ET hours, which can be calculated by minus two hours from daily sunshine hours. Now, ET in a region can be calculated from Equations (2) and (3). The steps for regional ET estimation can be summarized as follows: 1) Calculating the incoming net radiation Rn, sensible heat flux H, and soil heat flux G. 2) Developing ET models for bare soil and dense vegetation, and calculating vegetation cover-degree and instantaneous regional ET respectively. 3) Estimating the regional evapotranspiration of the area concerned. ET estimation model for a certain region is illustrated in Figure 1. Figure 1 Flowchart of evapotranspiration estimation based on remote sensing model 3 Parameter specification The model illustrated (Figure 1) includes three parts: bare soil ET, dense vegetation ET and vegetation cover-degree estimation. There are sub-models for incoming net radiation, sensible heat flux and soil heat flux and others in models for bare soil ET and dense vegetation ET. The parameters in sensible heat flux and soil heat flux sub-models are different under the conditions of bare soil and dense vegetation. Thus, parameter selection is the key procedure. 3.1 Surface net radiation Solar radiation is the main energy source of evapotranspiration and the energy budget of land surface can be expressed as where Q is solar radiation, is surface albedo, and is Stefan-Boltzmann˘s constant. is long-wave radiation of atmosphere, is atmosphere emissivity, and is vapour pressure at temperature Ta, (hPa). is long-wave radiation of earth surface, and Ts is radiometric surface temperature. Surface albedo distribution is derived from remote sensing data, because different land surface features and land-cover conditions cause anisotropic surface albedo distribution. The basic process is that the broadband planetary albedo is calculated from narrowband planetary albedo and then the land surface albedo is derived from broadband planetary albedo. In this paper, a regression method is applied to calculate surface albedo using 1, 2 narrowbands planetary albedo of AVHRR data. The experiential equation and coefficients are cited from reference [12]. The broadband planetary albedo (?p) is linear with surface albedo (?) measured in the field at the same time. The linear relationship between and ? is regressed as Thus surface albedo can be calculated by equation (5) using broadband planetary albedo, which can be derived from 1, 2 narrowbands planetary albedo of AVHRR data. 3.2 Soil heat flux (G) It has been proved that heat conduction entering the substrate can be written as the product of proportional function, ?, and net radiation. ?for bare soil and dense vegetation areas can be approximated separately by a constant and an expression composed by surface temperature, NDVI and ?[13,14], thus the following formula can be derived. 3.3 Sensible heat flux (H) The sensible heat flux, H, can be written in a turbulent type as follows: where is thermal capacity of atmosphere, and Ta is air temperature at reference height. and Ta can be calculated from meteorological measurements. The temperature at evapotranspiration surface (Tc) may take land surface temperature (Tcs) and plant canopy temperature (Tcv) for bare soil and dense vegetation areas respectively. Tcs and Tcv can be calculated by the brightness temperature of 4, 5 bands of NOAA data[15,16]. The aerodynamic resistance (ra) is very complex, and thus the term ra will be defined differently when applied to different conditions. The aerodynamic resistance is defined as ra0 in the conditions of neutral atmospheric stability, and a correction is made on the aerodynamic resistance in the conditions of neutral atmospheric instability. The improved aerodynamic resistance , , can be written in terms of stability coefficients (?) as In addition to the aerodynamic resistance, there is an excess resistance (rbh), which has the same order of magnitude with the improved aerodynamic resistance in dense vegetation area[9]. Thus, the aerodynamic resistance over dense vegetation area is a sum of the improved aerodynamic resistance and excess resistance, while over bare soil area it reduces to the improved aerodynamic resistance. To calculate the aerodynamic resistance over dense vegetation area and bare soil area, we need the parameters ra0 , ? and rbh, which can be expressed as formulae (9), (10) and (11). ?Aerodynamic resistance (ra0) where x is the reference height when meteorological measurements are available (2 m in this analysis), k is Von Karman˘s constant (value of k =0.4), n is a coefficient chosen as 2.5[17] (see for example Shuttleworth 1985), and h is plant height (m), chosen as 0.2 m for grassland and 0.8 m for shrubs in this research. z0˘ is the effective roughness of the substrate, for bare soil z0˘ is commonly taken as 0.01 m, and z0 is surface roughness. The ¨d〃 is zero plane displacement, and u is the wind speed at the reference height x. For dense vegetation area the value of d = 0.63h and the value of z0 = 0.13h are taken. ?Stability coefficients (?) where g is acceleration of gravity (9.8 m/s), and the coefficients? is commonly taken as 5. T0 is taken as the average value of canopy temperature (Tcv) and air temperature (Ta). In a similar way, TS0 is taken as the average value of land surface temperature and air temperature. In the conditions of neutral atmospheric stability, for a plant height (h) of 0.2 m and wind speed (u) of 2 m?s-1, this gives rac=149.93 s?m-1 over dense vegetation area and rac=87.73s?m-1 over bear soil area. ?Excess resistance (rbh) where u* is the friction velocity, which is given by the expression: u* = ku2 / ln ((z-d) / z0. The ¨u2〃, the wind speed at 2 m, yields a relationship between u2 and u10: u2=0.72u10, where u10 is the wind speed at 10 m. For plant height of 0.2 m and wind speed (u) of 2 m?s-1, this gives excess resistance (rbh) =21.38 s?m-1 over area covered with dense vegetation. 3.4 Vegetation cover-degree (f) The regional cover-degree of vegetation (f) yields a relationship between f and NDVI in the form of[18] where NDVImax and NDVImin are the maximum and the minimum values of NDVI in the whole growing season of vegetation (0.9 and 0.005 are taken respectively in this analysis). Thus, we can calculate the regional evapotranspiration with meteorological data and the parameters, such as surface temperature, albedo and cover-degree of vegetation, which are derived from remote sensing data. 4 Analysis of results 4.1 The study area and data selection The study area includes five provinces and autonomous regions of Northwest China (Xinjiang, Qinghai, Gansu, Ningxia and Shaanxi) and 3 counties of northern Inner Mongolia (Alxa, Ih Ju and Bayannur). This region covers a wide area from 31o57˘N to 49o33˘N and from 73o21˘E to 111o40˘E including the humid, semiarid and arid climatic zones. Due to the variation of regional climate and the types of land cover, the variability of surface evapotranspiration is significant. In this paper, the analysis is carried out for the following data: 1) Clear-sky NOAA/AVHRR data in 1B form, at 11 a.m. on July 25,1995 which comes from the Weather Bureau of China. 2) The Digital Vegetation Map of China, scale: 1: 4,000,000, provided by the State Key Lab of GIS in China. The projection is the same as the remote sensing data through image geometric correction supported by ARC/INFO. 3) The meteorological data, such as solar radiation, air temperature, sunshine percentage, absolute humidity, wind speed and surface albedo, of 45 standard meteorological observatories in the study area, which come from the Weather Center of China. 4.2 Analysis of results Supporting by GIS, the authors have produced a map showing the locations of those meteorological observatories using their latitudinal and longitudinal coordinates, and obtained digital images of meteorological elements by using Kriging method for interpolation. Calculations of the vegetation cover-degree and daily ET in the study area have been carried out by using the model for regional ET estimation, which is given in the last section. The results are shown in Figures 2 and 3. Figure 2 The result of vegetation cover-degree estimation over Northwest China Figure 3 The result of evapotranspiration estimation over Northwest China Table 1 Comparison of observed evapotranspiration with estimation of the model The features of vegetation cover-degree and daily ET over Northwest China are shown in the figures, from which we can draw conclusions as follows: 1) Except for the Ili Basin, Tacheng Basin and Altay Mountains, the zonal distributions of vegetation cover-degree in this region are obvious. Variation of vegetation cover-degree from Southeast to Northwest yields an increasing trend, which corresponds with the features of regional physical geography. It is clear that the distribution of vegetation belts, i.e., meadow, grassland and desert, are driven by meteorological conditions in this region. 2) Two centers of high daily ET value distribute from the Ili Basin to Tianshan Mountains and from Qilian Mountains to the upper reaches of the Yellow River and Hanzhong Basin. These two centers are located in humid or semi-humid region. Generally, the distribution of daily ET is in accordance with that of vegetation cover-degree, but they are different in detail. Besides vegetation cover-degree, energy, soil moisture, precipitation and other factors affect the distribution of daily ET as well. 3) The maximum value of daily ET is 4.56 mm, which is more than 40 times of the minimum value (0.11 mm). It is clear that the variability of daily ET is significant in this region. 4.3 Analysis of precision Due to the lack of the daily ET data observed at the same time when the satellite pass by, the data measured in the last ten days of July, 1995 have been used to compare with the estimated value so as to examine the precision of the model. The spots were chosen in terms of different vegetation coverage conditions, which influenced the daily ET. The authors selected the daily ET values of the pixels, which correspond to the latitudinal and longitudinal coordinates of observed spots. The results of comparison are shown in Table 1, which indicates that the maximum relative error is 20.0%, the minimum relative error is 12.8%, and the averaged relative error is 16.1%. The results show that the estimation model is fit to calculate the regional ET, because the estimated values in different vegetation coverage conditions are all close to the observed values. 5 D

iscussion and conclusions 1) In this paper, the ET estimation models for dense vegetation and bare soil are presented and the parameters for the models are discussed, based on the features of surface cover. Combined with vegetation cover-degree data, a model for regional ET estimation over the heterogeneous landscape is derived. The result of a case study of Northwest China shows that the accuracy is high. Thus, the model is fit to estimate regional ET over a large area. 2) Different expressions of G and ra are given in terms of different vegetation coverage. The excess resistance rbh is included in ra calculation over vegetation covered area, thus the precision of ra is improved. 3) The main feature of ET over Northwest China is that the value of regional ET synthetically reflects the distribution of surface energy, soil moisture and vegetation coverage. The two centers of high daily ET values are the areas from the Eli Basin to Tianshan Mountains and from Qilian Mountains to the upper reaches of the Yellow River and Hanzhong Basin. The variability of daily ET is significant, and the maximum value is more than 40 times of the minimum value in this region. There are some errors in the surface temperature derived form NOAA/AVHRR data, and the problems of scale transformations are not completely solved in meteorological data for regional-scale application. In addition, further research on the complexity of ra and vegetation-soil interaction are necessary. These are the limiting factors to the precision of the models and are the objects to be studied in the future. References

关键词： evapotranspiration; remote sensing; vegetation cover-degree; Northwest China

