地理学报(英文版) 2003年第13卷第4期

Dynamic analysis of evapotranspiration based on remote sensing in Yellow River Delta

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Evapotranspiration (ET) is an important parameter for water resource management. Compared to the traditional ET computation and measurement methods, the ET computation method based on remote sensing has the advantages of quickness, precision, raster mapping and regional scale. SEBAL, an ET computation model using remote sensing method is based on the surface energy balance equation which is a function of net radiance flux, soil heat flux, sensible heat flux and latent heat flux. The former three fluxes can be computed through the parameters retrieved from remote sensing image, then the latent heat flux can be obtained to provide energy for ET. Finally we can obtain the daily ET. In this study SEBAL was applied to compute ET in the Yellow River Delta of China where water resource faces a rigorous situation. Three Landsat TM images and meteorology data of 1999 were used for ET computation, and spatial and temporal change patterns of ET in the Yellow River Delta were analysed.

Dynamic analysis of evapotranspiration based on remote sensing in Yellow River Delta PAN Zhiqiang, LIU Gaohuan, ZHOU Chenghu (State Key Laboratory of Resource and Environment Information System, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China) 1 Introduction Evapotranspiration (ET) is an important part of the hydrologic cycle. Water resource is becoming the precious natural resource and how to manage water resource wisely is posing a great challenge. Crop irrigation is a major water consumer in agricultural regions. With the decrease of water resource, we should take more efficient measures for irrigation management according to the crop demands to achieve the sustainable utilization of water resource. ET is an important parameter for the water resource management. Through the prediction of ET, not only can we know the water wastage of the land surface, but also there is important reference information for the irrigation supply planning, water rights regulation, and hydrologic study (Bastiaanssen et al., 2000). There are many traditional ET computation methods which generally include two steps: First, calculate reference ET (ETr), and second, ET equals to ETr multiplied by crop coefficient Kc which varied for different crops and their growth stages (Ray et al., 2001). The ETr computation methods can be classified into three types: temperature methods, radiation methods and combination methods which are based on the original Penman combination equation that consists of two terms: the radiation term and the aerodynamic term (Jacobs et al., 2001). Moreover, ET can be measured quite accurately using apparatus such as weighing lysimeters (Liu et al., 2002) and TDR (Time Domain Reflectometry) (Mastrorilli et al., 1998), but all these ET computation and measurement methods are limited because they only provide point values of ET for a specific location and fail to provide ET on a regional scale. Actually, ET is highly variable in both space and time. Satellite images provide an excellent means for determining and mapping the spatial and temporal structure of ET. Remote sensing methods are attractive to estimate ET as they cover large areas and can provide estimates at a very high resolution (Kite et al., 2000). Some researchers developed several Remote Sensing methods to compute ET. Granger (2000) used satellite-derived feedback mechanism to compute ET. Choudhury (2000) developed a biophysical model which linked the water, energy and carbon processes by using satellite and ancillary data to quantify ET and biomass production. Bastiaanssen et al. (1998) developed a model named SEBAL which is comprised of 25 submodels. SEBAL was used by many researchers to study ET (Caselles et al., 1998; Medina et al., 1998; Timmermansl et al., 1999; Bastiaanssen et al., 2000; Chemin et al., 2001). In this study we use the SEBAL model to compute ET for the Yellow River Delta (YRD) of China, and make spatial and temporal analysis of ET. The Yellow River is the main fresh water source for the YRD people, and the total water amount which gets to this region from the Yellow River i s decreasing in recent years. This study is helpful for the proper utilization of water resource of the Yellow River Delta. 2 Materials 2.1 Study area Dongying Municipality of Shandong Province of China, which lies between 118o00´-119o20´E and 36o50´-38o10´N, is located at the mouth of the Yellow River (Figure 1), and its area accounts for 93% of the Yellow River Delta. Dongying Municipality is subdivided into five administrative units, i.e., Guangrao county, Dongying district, Lijin county, Kenli county and Hekou district. The total area of Dongying Municipality is nearly 800,000 ha by 2000. The area has a monsoon climate of the warm-temperate zone. Four seasons can be distinguished: a dry cold winter, a dry warm spring, a humid hot summer and an autumn with temperate conditions. The annual mean temperature is 11.7-12.6oC. The annual average precipitation is 530-630 mm, of which 70% is concentrated in summer. 2.2 Materials The materials used in this study can be classified into two groups: 2.2.1 Landsat TM images Three Landsat images are used in this study: TM5 image which was taken on May 2, 1999 (10:30 am), TM5 image taken on June 25, 1999 (10:30 am) and TM5 image taken on August 28, 1999 (10:30 am). The images were all treated with geometric rectification and clipped using YRD border. Image1, image2 and image3 are the simplified name of the three images, T1, T2, T3 are the time when the three images were taken, and ET1, ET2, ET3 are the ET maps computed from the three images. 2.2.2 Meteorologic data During the days when the images were taken, the following meteorologic data are needed: air temperature, wind speed, solar radiation, precipitation and vapor pressure. All the data are hourly data. 3 Methods SEBAL (Surface Energy Balance Algorithm for Land) is a model for ET computation based on remote sensing image and weather data using surface energy balance equation (equation (1)). In the surface energy balance equation, the net radiation flux Rn represents the radiant energy absorbed by the surface of the earth minus the amount of radiation released from the surface. This heat is divided into three parts: soil heat flux G, sensible heat flux H and latent heat LE. Rn = LE + G + H (1) The SEBAL model solves the surface energy balance equation by considering Rn, G and H successively. The LE flux that provides energy for ET is the residual of the energy balance equation. Since the satellite image provides information for the overpass time only, SEBAL computes an instantaneous ET for the image time. Daily ET can be computed further by using meteorologic data. If selecting some images properly, the seasonal ET can also be computed. 3.1 Net radiation flux The net radiation flux Rn at the surface represents the actual radiant energy available at the surface. It is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes. It is computed using equation (2). Rn = (1 - ?琢)Rs(in) + RL(in) - RL(out) - (1 - ?着0)RL(in) (2) where Rs(in) is the incoming shortwave radiation (W/m2), ?琢 is the surface albedo (dimensionless), RL(in) is the incoming longwave radiation (W/m2), RL(out) is the outgoing longwave radiation (W/m2), and ?着0 is the surface thermal emissivity (dimensionless). 3.2 Soil heat flux Soil heat flux G is the rate of heat storage into the soil and vegetation due to conduction. It is computed using empirical equation (3). G/Rn = Ts/?琢(0.0038?琢 + 0.0074?琢2)(1 - 0.98NDVI4) (3) where Ts is the surface temperature (oC), ?琢 is the surface albedo, NDVI is the Normalized Difference Vegetation Index (dimensionless), and Rn is the net radiation flux (W/m2). 3.3 Sensible heat flux Sensible heat flux H is the rate of heat loss to the air by convection and conduction due to a temperature difference. It is computed using equation (4). H = (?籽×Cp(dT)/rah (4) where ?籽 is air density (kg/m3), Cp is air specific heat (1004 J/kg/K), dT (K) is the temperature difference (T1-T2) between two heights (Z1 and Z2, usually 0.1 m and 2 m), and rah is the aerodynamic resistance to heat transport (s/m). Equation (4) is difficult to solve because there are two unknown variables, rah and dT. To facilitate this computation, SEBAL model utilizes two "anchor" pixels to fix boundary conditions for the energy balance. These are the "hot" and "cold" pixels that are located in the area of interest. The "cold" pixel is selected as a wet, well-irrigated crop surface having full ground cover by vegetation where ET is assumed to be reference ET (ETr). The "hot" pixel is selected as a dry, bare agricultural field where ET is assumed to be zero. Using these two pixels the sensible heat flux can be computed by an iterative solution of standard heat and momentum transport equations including pixel-based Monin-Obukhov stability corrections (Figure 2). 3.4 Instantaneous ET and daily ET Instantaneous ET can be computed using equation (5): ETinst = 3600■ (5) where ETinst is the instantaneous ET (mm/hr), 3600 is the time conversion from seconds to hours, and ?姿 is the latent heat of vaporization or the heat absorbed when a kilogram of water evaporates (J/kg). The reference ET fraction (ETrF) is defined as the ratio of the computed instantaneous ET (ETinst) for each pixel to the reference ET (ETr) computed from weather data: (6) ETrF is similar to the well-known crop coefficient, Kc. ETrF is used to extrapolate ET from the image time to 24-hour or longer periods. Finally, the ETday (mm/day) can be computed using equation (7). ETday = ETrF×ETr_24 (7) where ETr_24 is the cumulative 24-hour ETr for the day of the image. It is calculated by adding the hourly ETr values over the day of the image. 4 Results 4.1 Energy fluxes and daily evapotranspiration Net radiation flux Rn, soil heat flux G and sensible heat flux H are determined by many factors such as solar radiation, land cover, etc. Because the three images were taken at different time, obviously solar radiation and land cover are different, so the net radiation flux Rn, soil heat flux G and sensible heat flux H of the three im ages are also different (Figures 3 and 4). Figure 3 shows the frequency curves of different surface energy fluxes and daily ET, and Figure 4 shows the statistical parameters derived from Figure 3, including maximum, minimum, mean and standard deviation values. 4.2 Spatial change of evapotranspiration The ET maps of the Yellow River Delta were computed from three images (Figure 6). To understand the ET maps clearly, first we should know the land cover of different images. The main crops of YRD are winter wheat, maize, cotton, rice and bean during the year (Figure 5). For image 1, the land was covered only by winter wheat and grass. The winter wheat was at its mature growth stage, and grass was at its seedling growth stage. So we can find that winter wheat has higher ET value which is located in the southern and southwestern parts of YRD (ET1 map of Figure 6). For image2, land cover were maize, cotton, rice, bean and grass, winter wheat was harvested several days before. Maize, cotton, bean and rice were at their seedling growth stage. So we can find that in the southern part which has lower ET value was the harvested land where winter wheat was planted before, and all the other crop area which had higher ET value was mostly located in the northwestern part of YRD (ET2 map of Figure 6). For image3, land was covered by maize, cotton, rice, bean and grass, and all the vegetables were at their mature growth stage, so most part of YRD has higher ET value except the land for residents and the land where less vegetables grow (ET3 map of Figure 6). In each ET map the highest ET value appears in all types of water body including rivers, reservoirs, etc. 4.3 Temporal change of evapotranspiration To compare how ET changes during the three times, we combine the three ET maps into one image which has 3 layers (ET1, ET2, ET3), with ET1, ET2, ET3 as red, green, blue band respectively (Figure 7). We can find that because ET changes with time it shows different colors in different regions, and the different colors show that the pattern of ET change is different. To understand the pattern of ET change that the different colors represent, we sample about 50 points randomly for each color region, statistical result of the samples is shown in Table 1, and Figure 8 is derived from Table 1. In Figure 7 there are 8 distinct color areas, for color C1 values of ET1 and ET3 are both high and are almost the same, and values of ET2 are lower than those of ET1 and ET3. Color C3 indicates that the ET values are all very low at different time and the value of ET2 is higher than that of ET1 and ET3. Color C4 represents that ET values are almost the same at different time and the ET values are high. We can also know the implication of other colors. This analysis is helpful for us to understand the reason why the different color regions appear. We can also distinguish some land cover according to the ET change pattern, for example, color C1 area is mostly the wheat-maize rotation region, color C3 area is residential region and bare land, color C4 area is water body and color C7 area is cotton region. 4.4 Validation Validation for the ET computation result is an important issue, and it is also a complex issue. Some researchers have done this work in their studies. Allen et al. (2001) compare the predicted ET computed using SEBAL model in the Bear River Basin of Idaho, Utah of USA with lysimeter measurements of ET, and obtained good results with monthly differences averaging ±16%, but with seasonal difference of only 4% due to reduction in random error. Kite et al. (2000) compared ET estimates from different methods and the daily ET difference for SEBAL is -18%. Unfortunately, there are no crop ET records for the Yellow River Delta except the water evaporation records. The differences of water evaporation for the three images are -9.5%, -14.7% and -13.9% respectively, and the average difference is -12.7%. Although ET of water is different from ET of crop we can still find that the SEBAL model has a good precision for ET computation. 5 Discussion In this study, SEBAL, an ET computation model based on Remote Sensing, was used to compute ET in the Yellow River Delta of China. Three TM images of 1999 were used, and the ET spatial and temporal changes were analysed. Because the ET maps calculated from the three images can represent the ET change from late spring to early autumn in the Yellow River Delta, we can understand the rule of ET change in this region better, thus it is very useful for the determination of the moisture state, irrigation scheduling and irrigation evaluation. The coverage of crops in this region is very complicated during the year, through this study, it is helpful for us to select images for different crops in different regions of the Yellow River Delta to compute seasonal ET further, and this is useful for the water resource management. ET computation method based on remote sensing has many advantages that the traditional ET computation methods do not have, such as regional scale, raster mapping, etc. SEBAL model is a good method to compute ET. The spatial and temporal resolutions are both important for ET computation. TM has higher spatial resolution but its temporal resolution is lower (16 days), while NOAA AVHRR has lower spatial resolution but its temporal resolution is higher (1-2 day). Further research should focus on how to combine TM image and NOAA AVHRR image to get both better spatial resolution and better temporal resolution for the ET computation.

关键词： evapotranspiration; remote sensing; Yellow River Delta