Spatial distribution and change trend of land surface evaporation and drought in Sichuan Province (China) during 2001 to 2015

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ABSTRACT

With the rapid development of economic situation, global warming and population growing, drought happened in many areas. Based on linear dual source remote sensing model we establish the modified hybrid linear dual-source’s remote sensing evaporation model to simulate the Sichuan Province actual evaporation. Then we calculate the potential evaporation by using the Hargreaves formula. In addition, we analyze evaporation and drought trend of Sichuan province. This study showed that: (1) the actual variation trend of evaporation in Sichuan Province is decreasing from 2001 to 2015. The actual evaporation in the east is higher than that in the west regions, and in the south is higher than that in the north regions. (2) The value of potential evaporation fluctuates is not obviously in every season. According to the spatial distribution, the potential evaporation distribution is decreasing from south to north. (3) The evaporation of drought index shows an upward trend, but the fluctuation phenomenon of Sichuan Province in the past seasons is not obvious. This climate research provide the basis for the prediction and guidance of agricultural activities in the region.

Introduction

Evaporation is the total water vapor transported by vegetation and ground to the atmosphere, and is the important parameter of surface drought information. According to the global land evaporation trends, there are three views of increasing, decreasing and unchanging. Many scholars show that: evaporation has an increasing trend in many regions in recent decades (Brutsaert & Parlange, 1998; Milly & Dunne, 2001; Wang & Liang, 2008; Zhang et al., 2010; Yin et al., 2013; Tian et al., 2012; Pengtao et al., 2016). Liu et al. (2008) show that pan evaporation has a significant downward trend during 1960–2005 in Xinjiang. On the contrary, the actual evaporation increased significantly in the same period. Bing et al. (2012) show that the total amount of land evaporation in China is increasing, and the July is the largest in the year. Pengtao (2016) shows that the Shan-Gan-Ning loess plateau has a slow upward trend during 2000–2012. Nevertheless, land surface evaporation of the study area has a decreasing trend.

The drought, which closely related to evaporation, is a kind of water supply for long-term less rainfall. Drought is a complex natural phenomenon, so it is difficult to measure accurately. There are many drought index, including rainfall, soil moisture index, etc. From water shortage, the soil moisture is the most important drought information parameter, but we could not get the observation data. Meteorologist uses the precipitation index in many aspects, and Palmer drought index (Palmer Z index, PDSI, PHDSD) is established based on precipitation indicators (Heim et al., 2002). Li et al. (2009) think that the standardized precipitation index (SPI) can well reflect the drought intensity and duration. The SPI is calculated by transforming precipitation data into lognormal values, then computing U statistics, as well as the shape and scale parameters of the gamma distribution. The incomplete gamma cumulative probability of an observed precipitation event is then calculated using the values obtained. It is possible to use the same drought index to reflect the drought condition in different time scales and different regions, so it is widely used. Monthly (or weekly) precipitation is used as the input data for the SPI. The monthly (or weekly) difference between precipitation and PET is used in the SPI. The SPI is calculated using a basic climatic water balance that is estimated at various time frames. Vicente-Serrano et al. (2010) proposed the standardized precipitation evaporation index (SPEI) that not only retains the characteristics of PDSI, but also has the advantage of SPI calculation, which is suitable for multi-scale and multi space comparison. Hu et al. (2016) proposed a new method of comprehensive drought index based on vertical mixed runoff model considering soil moisture. This model is a conceptual rainfall-runoff model that combines the

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mechanisms of runoff production in excess of infiltration at the soil surface with runoff formation on storage replenishment in the subsurface. Many scholars use different methods of estimating evaporation and different data to estimate global evaporation and drought (Han Y & Yaohui L, 2013). However, these methods require more parameters and complex calculation, which is not conducive to large-scale drought monitoring. Therefore, this paper based on the theory of water and energy balance, improving the linear dual source remote sensing evaporation model, optimize the parameters of the model, estimating evaporation using a more convenient method, and then analyzes temporal and spatial variation of drought in Sichuan Province in recent years. Evaporation is the principal method of removing water from a watershed, whereas transpiration is the method of removing water from vegetation or any other living surface that contains moisture. Evaporation through water bodies and soils is a term to describe the loss of water from the Earth’s surface to the atmosphere through a combination of evaporation and transpiration processes.

**Materials and methods**

**Materials**

We used the MOD13NDVI product data (2 standard data products) and MOD16 actual evaporation product data (4 standard data products). At the same time, meteorological stations data and radiation site data of Sichuan Province from 2001–2015 were obtained from the China Meteorological Data Sharing Network.

After MODIS data download, firstly, the MRT software was used for resampling and splicing, and then we use the vector data of Sichuan Province to cut the MODIS data. Meanwhile, meteorological stations and radiation site data also need to filtrate and interpolate. Finally, all processed data imported into the model to calculate.

**Methods**

**Hybrid linear dual source remote sensing evaporation Model**

In our algorithm, we use the modeling idea from Nishida et al. (2003). Considering the effect on evaporation by NDVI, the evaporation is divided into two components: bare soil evaporation and vegetation transpiration:

\[ f_v = \frac{NDVI - NDVImin}{NDVImax - NDVImin} \] (1)

\[ ET = f_vETv + (1 - f_v)ETS \] (2)

Where \( ET \) is total evaporation, \( ETv \) is fractional vegetation, and \( ETS \) is soil evaporation. Where NDVImax and NDVImin are NDVI of full vegetation (\( f_v=1 \)) and bare soil (\( f_v=0 \)).

In order to reduce the complexity of linear dual source evaporation model, we choose net radiation (\( R_n \)) and reciprocal of air temperature difference between day and night (\( 1/(T_{max} - T_{min}) \)) to simplify the evaporation model of bare soil. Evaporation from bare soil is a globally significant and crucially essential factor for farmers, particularly in irrigation management. Then there’s a soil-controlled stage, where the pace at which water can be carried to the surface, rather than atmospheric conditions, determines evaporation rate. The absorption and refraction of short-wave radiation, as well as the outgoing and incoming long-wave radiations, are all included in net radiation. The reciprocals can be used to indicate soil moisture content, and increased empirical coefficients \( a1 \):

\[ ETS = \frac{a1Rn}{T_{max} - T_{min}} \] (3)

Where air temperature difference between day and night can be obtained by meteorological data.

In order to simplify vegetation evaporation function, we think net radiation is the main controlling factor of vegetation evaporation, and then choose other important parameters, including air temperature (\( T \)), reciprocal of air temperature difference between day and night (\( 1/(T_{max} - T_{min}) \)). And we increased empirical coefficients \( a2 \) and \( a3 \):

\[ ETv = a2RnT + \frac{a3Rn}{T_{max} - T_{min}} \] (4)

In order to obtain the evaporation of vegetation and soil, we make \( a0Rn \) as a correction for the whole evaporation. The evaporation equation can be expressed as:

\[ ET = (1 - f_v) \frac{a1Rn}{T_{max} - T_{min}} + f_v(a2RnT + \frac{a3Rn}{T_{max} - T_{min}}) + a0Rn \] (5)

Considering that \( f_v \) is a function of NDVI, so we use NDVI to further simplify the hybrid linear dual source remote sensing evaporation model.
\[ ET = Rn(b0 + b1NDVI \times T + \frac{b2NDVI}{T_{\text{max}} - T_{\text{min}}}) + \frac{b3}{T_{\text{max}} - T_{\text{min}}}) \tag{6} \]

Where \( ET \) is the surface evaporation, \( Rn \) is net radiation, \( NDVI \) is normalized difference vegetation index, \( T_{\text{max}} \) is maximum air temperature, \( T_{\text{min}} \) is minimum air temperature, and \( b0, b1, b2, b3 \) are regression coefficients.

**Potential evaporation transpiration (PET)**

This study will use the Hargreaves (Zhao et al., 2004; Li et al., 2015) formula to estimate the potential evaporation in Sichuan Province, mainly taking into account the Hargreaves formula only need latitude, air temperature and air temperature difference between the three parameters. The Hargreaves equation is a straightforward evapotranspiration model with only a few easily available parameters: minimum, maximum, and mean temperature, as well as extraterrestrial radiation. The model is simple and easy to use. Hargreaves formula expressed as:

\[ \text{PET} = 0.0023Ra(T_{\text{mean}} + 17.8)\sqrt{T_{\text{max}} - T_{\text{min}}} \tag{7} \]

Where PET is potential evaporation transpiration, \( Ra \) is solar radiation that we estimate this component in equation:

\[ Ra = \frac{24}{\pi} \frac{Gscdr(\omega \sin(\phi) \sin(\delta)}{+ \cos(\phi) \cos(\delta) \sin(\omega s))} \tag{8} \]

Where Gsc is solar constant (4.92 MJ m\(^{-2}\)h\(^{-1}\)), \( dr \) is day distance coefficient, \( \omega \) is solar hour angle, \( \phi \) is latitude, \( \delta \) is declination of the sun. The electromagnetic radiation released by the sun is known as solar radiation, sometimes known as the solar resource or just sunshine. Evaporation and transpiration are water balance outflow events. The combined mechanism of surface water condensation, soil moisture evaporation, and plant transpiration is known as evapotranspiration (ET).

**Drought index**

Soil moisture, surface radiation, vegetation cover, and atmospheric factors, including air temperature, wind speed, and saturated vapor pressure (Ma, 2010) affect the variation of surface evaporation. The potential evaporation is the result of other factors under the condition of sufficient soil moisture. In this paper, the evaporation drought index (EDI) was defined to emphasize the effect of soil moisture on surface drying. EDI is defined as 1 minus the ratio of actual evaporation to potential evaporation, as follow:

\[ \text{EDI} = 1 - \frac{ET}{\text{PET}} \tag{9} \]

Where takes a value between 0 and 1. The closer the EDI value to 1, the more drought, the closer the value is to 0, indicating that the more humid.

**Results**

**Actual evaporation variation**

The actual evaporation of Sichuan Province in recent 15 years obtained by using the improved linear dual source remote sensing evaporation model. From Table 1 and Figures 1 and 2: (1) the average monthly evaporation in Sichuan Province shows the distribution of primary and secondary peaks. The main peak value appeared in July (accounting for 15.2%). The second peak occurred in October (accounting for 7.95%). The minimum value in December was only 28.95 mm, accounting for 4.87% of the total annual evaporation. (2) According to season, the highest is summer, followed by autumn, spring, and winter is the lowest (Han et al., 2014). The evaporation accounted of summer and autumn for more than 62.8% of the total annual evaporation. (3) Figure 1(b) shows that in the past 15 years, the actual evaporation in Sichuan Province shows a downward trend, and the interval of 2–3 year is a regular fluctuation. The magnitude of evaporation is a direct response to temperature and precipitation. In particular, the actual evaporation decreased year, more truly reflect the characteristics of climate change. From the annual curve, during 2002–2004 years, 2005–2007 years, 2008–2010 years and 2012–2015 years, the actual evaporation significantly decreased. According to the relevant scholars, Sichuan Province occurred continuously in the summer of 2006 and 2009–2010 years of severe drought (Bo, 2014). Sustained high temperature in Sichuan-Chongqing region in summer of 2006, it is the least precipitation year since 1951 (Liu et al., 2009). The lack of rain in summer directly led to the decline of the actual evaporation in 2006. Similarly, the downward trend of the actual evaporation in season and inter annual variability is also supported by the relevant literature during 2009–2010 (Ma et al., 2010; Chen et al., 2010; Han et al., 2013; Li et al., 2014; Han et al., 2014). (3) According to distribution map, the actual evaporation showed that appears on a diminishing scale from east to the west and from south to the north.

| Season         | Evaporation (mm) | Percentage (%) |
|----------------|------------------|----------------|
| Spring (3–5 months) | 191.73837        | 22.9975        |
| Summer (6–8 months) | 334.7819         | 40.1469        |
| Autumn (9–11 months) | 189.9614         | 22.6710        |
| Winter (12–2 months) | 118.3073         | 14.1866        |
Potential evaporation characteristics

From Table 2 and Figures 3 and 4, we can find that: (1) the potential evaporation in Sichuan is larger, and the monthly potential evaporation showed a single peak. The potential evaporation peak appeared in June, accounting for 11.15% of the total. The minimum appeared in December, accounting for 4.9% of the total. (2) The potential evaporation in spring and summer of Sichuan...
Province is large, which accounts for about 61.39% of the total annual potential evaporation. (3) There was little change in potential evaporation, which showed a decreasing trend in the past 15 years. (4) From the spatial distribution, the potential evaporation values in spring, autumn and winter significantly decreased from the south to the north, but in summer, it shows a decreasing trend from east to west.
Evaporation drought index

According to Figures 5 and 6: (1) the EDI value of drought index in Sichuan Province is larger, and the mean value is greater than 0.5. The EDI value shows a trend of “high-low-high”, and the low value is concentrated in 7–8 months, which shows that Sichuan Province has less drought in summer. The high concentration in 2–4 months and 10–12 months, indicating that spring, autumn, winter drought occurred more than 88.4%. The EDI has significant fluctuations during 2001–2015. During 05–06, 09–10, and 12–13 years curve increased rapidly, indicating that there was a greater degree of drought. The EDI trend shows a rising change, which explains that the drought in Sichuan has been increasing in recent 15 years. (3) From the distribution map, in winter, the drought in Sichuan Province is more serious, especially in northern Sichuan and southern Sichuan. In spring, the drought situation continued to increase in southern Sichuan and western Sichuan. In summer, other areas outside the north Sichuan area showed different degrees of improvement, especially changes significantly in south Sichuan. In autumn, the drought condition was better than that in summer.

Correlation analysis between EDI and soil moisture data

Soil water content and soil water holding capacity related to water supply in the process of crop growth. Therefore, soil moisture usually considered as an important parameter in drought monitoring. Observing indicators and indices that analyses changes in a region’s hydrological cycle is part of drought monitoring. The study of the relationship between EDI and soil moisture can further explain the feasibility of EDI.

When the soil moisture under water stress is lower than a critical value, crops will suffer from drought due to water shortage. When the humidity value decreases, it shows more vulnerable to drought. On the contrary, the bigger the EDI, the more severe drought conditions. Therefore, there is a negative correlation between the humidity value and the EDI drought index. As can be seen from Table 3, the maximum negative relationship value reached 0.5386 in 2006 of March.

Discussion

In this paper, the actual evaporation in Sichuan Province showed a decreasing trend. There are many possible reasons for this phenomenon: for example, the precipitation showed a downward trend and solar radiation is reduced due to increased aerosols. That is complex. What’s more, the actual evaporation in summer and autumn was greater than that in spring and winter, and it is mainly concentrated in the eastern Sichuan Basin. This is mainly caused by the uneven distribution of precipitation in time and space. The 80% of the precipitation is concentrated in summer and autumn and decreased from east to west. In addition, there was no obvious fluctuation of the potential evaporation in Sichuan Province. Because using the Hargreaves formula to estimate the potential evaporation, we use only one temperature factor, and the temperature changes were not significant. According to EDI, which is prone to drought in spring, autumn, and winter
In this study, the actual evaporation, potential evaporation, and evaporation drought index were analyzed only in season scale, and in the follow-up work, a detailed analysis was carried out on the ten days and months. Using only one temperature factor to estimate the potential evaporation has existed an error for evaporation changes complex. The follow-up study will introduce the precipitation factor to improve the inversion effect. The results of the two methods are compared with the P-M formula to find a more accurate and suitable method for estimating the area. In addition, in this paper, the use of MODIS data is easy to obtain, and the data to support a large area of drought monitoring, but the data is more susceptible to weather conditions, which will result in error analysis. For make up the inadequacy of the research, we will continue to improve in the later work and further improve the accuracy of the model.

### Conclusion

In this paper, the actual evaporation of Sichuan Province in nearly 15 years was obtained by using the improved mixed linear dual source remote sensing evaporation model. Through analysis temporal and spatial variation, we found that the actual evaporation in Sichuan Province showed a decreasing trend, and the
actual evaporation in summer and autumn was greater than that in spring and winter. The actual evaporation is mainly concentrated in the eastern Sichuan Basin. In the past 15 years, there was no obvious fluctuation of the potential evaporation in Sichuan Province. In summer, the potential evaporation was the highest, followed by autumn, spring and winter. The spatial distribution of potential evaporation presented a decreasing trend from south to the north, east to the west. During the year, the EDI concentration was 2–4 months and 10–12 months, which is prone to drought in spring, autumn and winter. The EDI showed an upward trend in the year, and the drought intensified.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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