Characteristics and cause analysis of flue-cured tobacco's water requirements during growth periods in low latitude plateau area, China

Na Fu, Xiaoyu Song, Lu Xia, Lanjun Li and Xiaogang Liu

ABSTRACT

This study aimed to identify the future changes in water requirements (ET_c) of flue-cured tobacco by comparing estimated ET_c values in the future with previous usage. This will provide a basis for estimating irrigation requirements, and help improve agricultural water use efficiency in the future. The Penman–Monteith equation and the single-crop efficient method were used to calculate the flue-cured tobacco ET_c, net irrigation requirement (*IR*) and net irrigation requirement index (*IDI*) for the period 1956–2015, and the four Intergovernmental Panel on Climate Change (IPCC) AR5 emission scenarios were used to estimate ET_c for two future periods (2046–2065 and 2081–2100) in the central Yunnan Province, China. The results showed that the *IDI* gradually decreased, along with the growth of flue-cured tobacco. The ET_c, *IR* and *IDI* values increased with latitude in central Yunnan Province. Furthermore, the variations in the ET_c over the whole growth period in the mid-21st century and late-21st century also tended to increase with latitude. In addition, based on the influence of climate variation on the ET_c as assessed by a principal component analysis, precipitation was the main factor affecting flue-cured tobacco growth. This study contributes to the establishment of suitable irrigation systems for flue-cured tobacco at every growth stage in central Yunnan Province.

Key words | flue-cured tobacco, low latitude plateau area, meteorological factors, principal component analysis, water requirement

Na Fu
Xiaoyu Song (corresponding author)
Lu Xia
Lanjun Li
State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China,
Xi'an University of Technology,
Xi'an 710048,
China
E-mail: *songxy@xaut.edu.cn*

Xiaogang Liu
Faculty of Modern Agricultural Engineering,
Kunming University of Science and Technology,
Kunming 650500,
China

INTRODUCTION

Flue-cured tobacco, also known as fire tube flue-cured tobacco, is native to Virginia, USA. It is named after the process whereby picked tobacco leaves are roasted in a fire tube. Flue-cured tobacco is the main raw material for the cigarette industry, and China is the largest tobacco growing area in the world. As the country with the highest yield of flue-cured tobacco in the world, China's yield accounts for 52% of the total worldwide flue-cured tobacco yield. The low latitude plateau area, which has both a high altitude and a low latitude, is the tobacco planting area in China. The area and yield of flue-cured tobacco in the low latitude plateau area accounts for more than 40% of China's total area (Rural Social Economic Investigation Division National Bureau of Statistics of China 2008). Climatic conditions are the main environmental factors that affect the yield and quality of flue-cured tobacco (Karaivazoglou *et al.* 2007; Chen *et al.* 2010; Wu *et al.* 2013). Yunnan Province is a typical low latitude plateau area in southwest China (21.14–29.25°N and 97.52–106.19°E), with an average elevation of 1,890 m (Zhu *et al.* 2016). The natural geographical environment is complex and unique, and can be affected by the southwestern monsoons, the southeastern monsoons and cold air abnormalities from northern China (Wang 1996; Huang 2011; Zomer *et al.* 2015). Furthermore,

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Yunnan Province has experienced substantial interannual climate variability in recent years (Gu *et al.* 2016).

Central Yunnan Province, which includes Yuxi, Chuxiong, Kunming and Yuanmou, is the main production area for flue-cured tobacco in the low latitude plateau area. Because of the unique topographic elements and climatic characteristics, the flue-cured tobacco from this area is of good quality. However, in recent years, Yunnan Province has experienced large drought periods which negatively affected the yield and quality of its flue-cured tobacco. The average temperature between April and August for 2000–2010 was 19.42°, which was 0.32° higher than the same period between 1979 and 1989. Over the same period, the average daily sunshine hours declined by 7.1 min and the average daily precipitation increased by 0.086 mm (Huang & Zhang 2013). The water resource crisis under global warming conditions will be more serious in China in the 21st century. Therefore, it is necessary to optimize the water resources in central Yunnan Province and understand the ET_c of flue-cured tobacco to provide a theoretical basis for the preservation and development of the flue-cured tobacco industry.

Much research has been conducted on the variations in crop water consumption and irrigation water demands under climate change conditions. Cong *et al.* (2010) investigated the impact of the predicted climate change using the HadCM3 model and the Intergovernmental Panel on Climate Change (IPCC) scenarios predicted by COMMIT, SRA1B, SRA2, and SRB1 for winter wheat growth and water use near Beijing under different irrigation treatments. The growth of winter wheat was simulated using the CERES model. Nkomozepi & Chung (2012) used the global climate model and CROPWAT models to analyze and forecast maize ET_c and IDI values in the natural agricultural ecological zone of Zimbabwe. Wang *et al.* (2015) used meteorological data and the statistical downscale results of the HadCM3 atmospheric circulation model under A2 and B2 scenes. The effect of climate change on rice water demand was then studied using the ORYZA2000 model to simulate irrigation modes under both flooded and intermittent conditions. Fares *et al.* (2017) used the Irrigation Management System model to calculate the optimum irrigation requirements for the baseline period (1986–2005) and two future periods (2055s and 2090s), which were subject to a combination of five and seven temperature and precipitation levels, respectively. In recent years, crop water requirements and their response to climate have become important in analyzing water resources, but research on the ET_c values for flue-cured tobacco is still at the primary stage (He 2004; Zheng *et al.* 2015; Zhou *et al.* 2018). There have been few studies on the ET_c, characteristics, rainfall utilization efficiency, and the relationship between water requirement and climate factors during the flue-cured tobacco growth period. Furthermore, there is little information available about flue-cured tobacco ET_c and their response to climate change for any of the individual growth stages in the flue-cured tobacco production areas.

Here, flue-cured tobacco was investigated based on the daily surface meteorological data from four meteorological stations, at Chuxiong, Yuxi, Yuanmou and Kunming, in central Yunnan Province from 1956 to 2015. In this study, the Food and Agriculture Organization of the United Nations' Penman–Monteith method and single-crop coefficient method were combined to calculate the ET_c, IR and IDI. The spatial and temporal variations in ET_c during the flue-cured tobacco growing season for the periods 1956–2015, 2046–2065, and 2081–2100 were analyzed in central Yunnan Province. Additionally, principal component analysis was used to study the impact of meteorological factors on the IDI. The purpose of this study was to offer guidance that could be used to establish suitable irrigation systems for every growth stage and to provide basic data and a theoretical basis for a rational water distribution and scientifically based water resource management program for flue-cured tobacco in central Yunnan Province.

MATERIALS AND METHODS

Research areas

The study area was located in central Yunnan Province, including Kunming, Yuxi, Chuxiong, Yuanmou and other regions, which is the main flue-cured tobacco planting area (Figure 1). The area is 2,300–2,600 meters above sea level, with an area of 6,700,000 km^2. Soil types mainly include red, paddy and purple. The study area has a low-latitude mountain plateau monsoon climate, with the annual precipitation divided into wet and dry seasons in

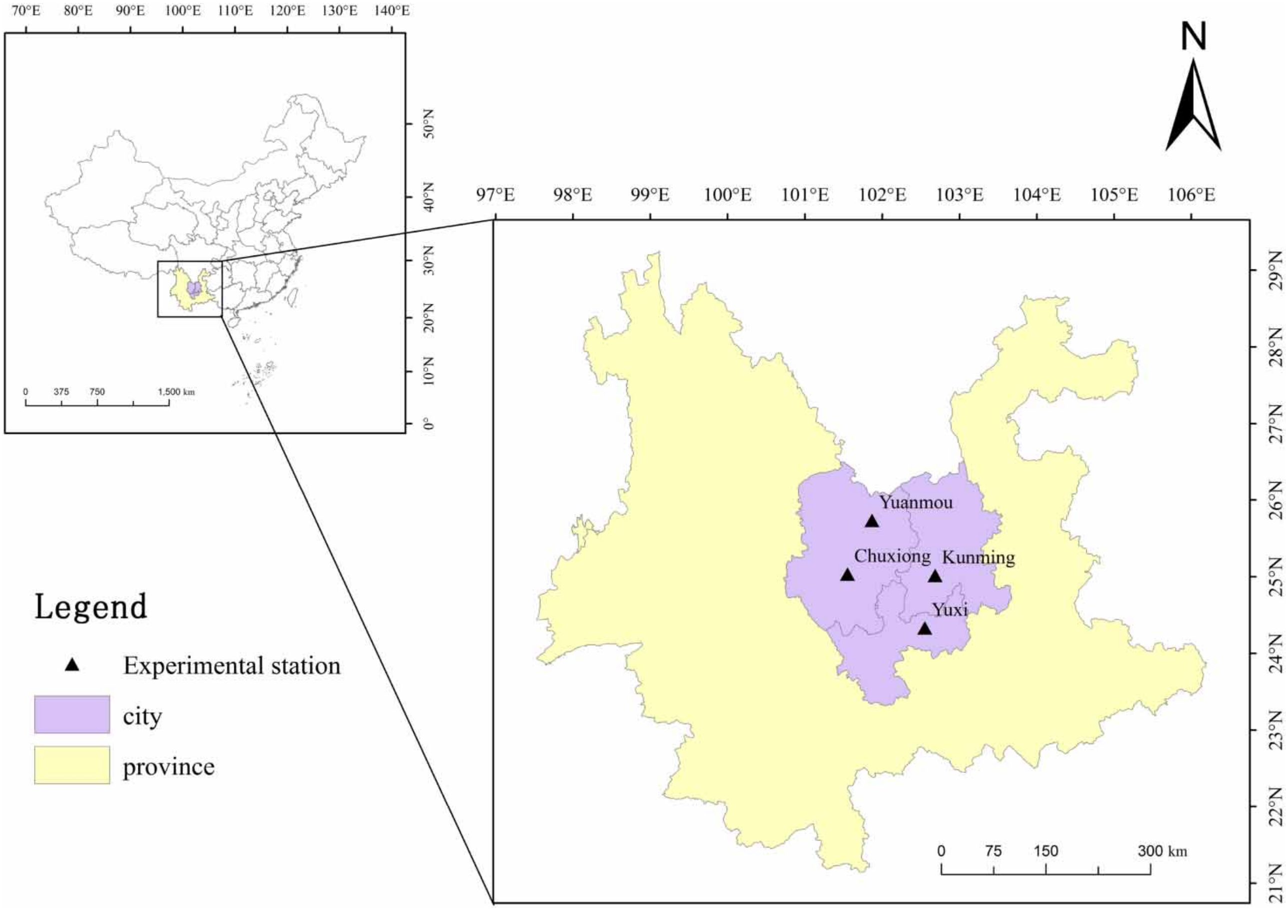

Figure 1 | Geographical information map of central Yunnan Province.

which the precipitation is very unevenly distributed. The rainy season starts in late May and ends in mid-October (Yan *et al.* 2018). The average annual precipitation is 1,020 mm, and sunshine duration is short. The temperature is low in summer, but it is warm and dry in winter (Chen *et al.* 2015). The annual average temperature ranges from 5 to 25 °C. The frost-free period was more than 300 days per year between 1956 and 2015. Table 1 shows the general soil types and principal climatic factors in central Yunnan Province. Figures 2 and 3 show the temporal and spatial distributions of the daily means for the principle climate characteristics in central Yunnan Province.

Data sources

The daily meteorological data for 1956–2015 was recorded by meteorological stations at Kunming, Yuxi, Chuxiong and Yuanmou in the flue-cured tobacco production area in

Table 1 | General soil types and a daily average summary of the principle climate characteristics for central Yunnan Province (based on 1956–2015 data)

Region	Soil type	Precipitation (mm)	Wind speed (m/s)	Temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)	Relative humidity (%)	Sunshine duration (h)
Kunming	Red	2.77	2.15	15.11	10.49	21.07	71.68	6.29
Yuxi	Lateritic red	2.55	1.71	16.11	11.33	22.86	73.86	5.85
Chuxiong	Yellow brown	2.31	1.69	16.03	10.85	22.42	69.51	6.09
Yuanmou	Dry red	1.72	2.15	21.65	16.08	28.78	56.02	7.15

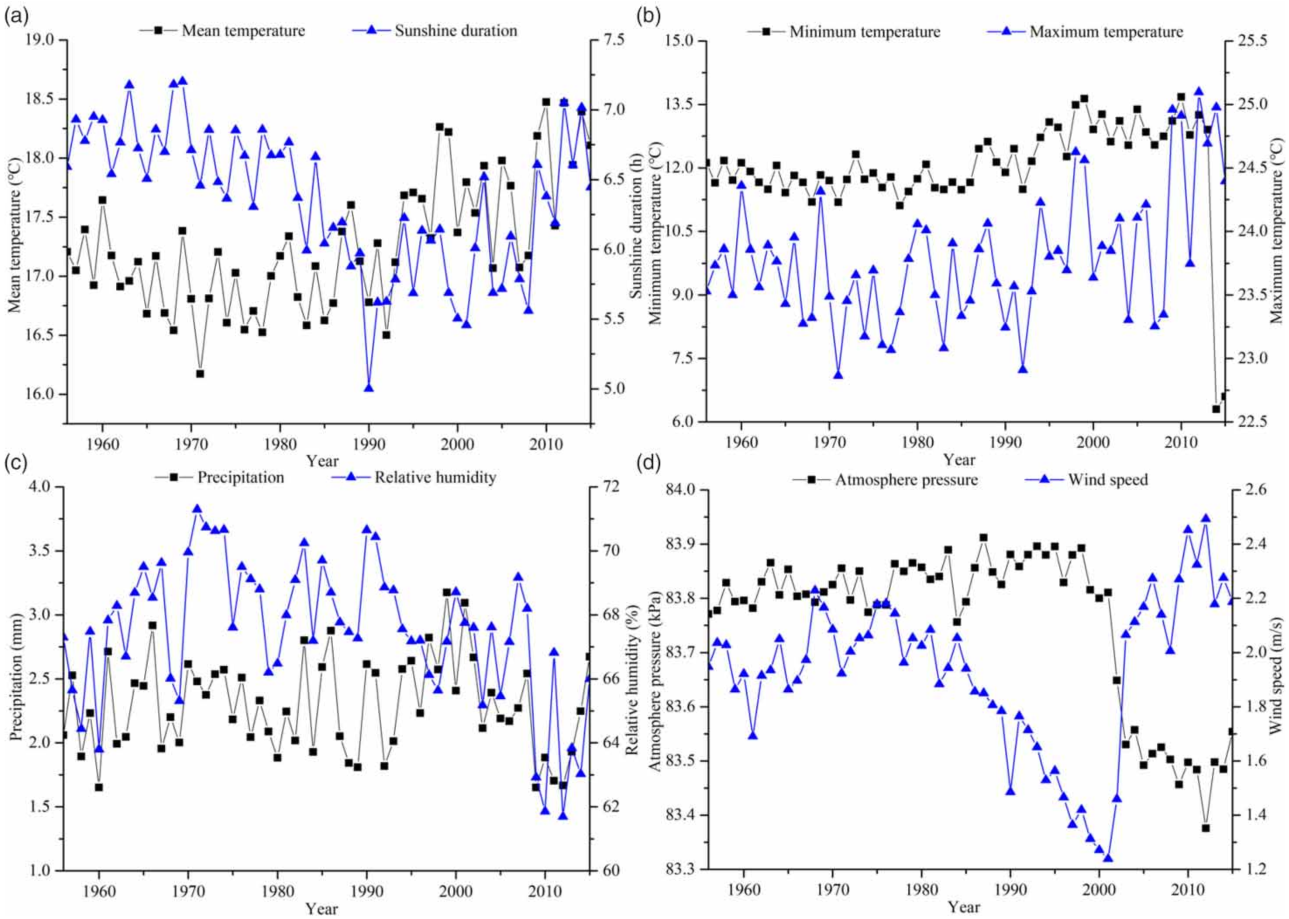

Figure 2 | Temporal distribution of the daily means for the principle climate characteristics in central Yunnan Province (based on 1956–2015 data): (a) mean temperature and sunshine duration; (b) minimum and maximum temperatures; (c) precipitation and relative humidity; and (d) atmosphere pressure and wind speed.

Yunnan Province. Data are from the China Meteorological Science Data Sharing Service network. Data included daily mean temperature, daily minimum temperature, daily maximum temperature, daily precipitation, daily average relative humidity, sunshine duration, the average daily mean vapor pressure and wind speed.

IR and *IDI* of flue-cured tobacco

IR is an important reference for irrigation water consumption in the agricultural production of flue-cured tobacco (Toureiro *et al.* 2017). The *IR* value of a crop is the difference between the crop water demand and the effective precipitation during the growth stage. The *IDI* is the ratio of net irrigation water demand to the crop's ET_c. The index reflects the dependence of crop growth on irrigation and the relationship between drought and crop growth to a certain extent (Seidel *et al.* 2017). The formulae are as follows:

$$IR = ET_c - P_e \tag{1}$$

$$IDI = IR/ET_c \tag{2}$$

where P_e is the daily effective precipitation (mm/day). The effective precipitation of flue-cured tobacco refers to the amount of water used to meet crop evapotranspiration (Marek *et al.* 2016), but it does not include surface runoff or water seepage into the roots of the crop. Effective precipitation is a strong basis for formulating irrigation and drainage plans, irrigation systems and irrigation water quotas for agricultural production. During the actual crop growth process, many factors affect effective precipitation. This study used the calculation method used for effective

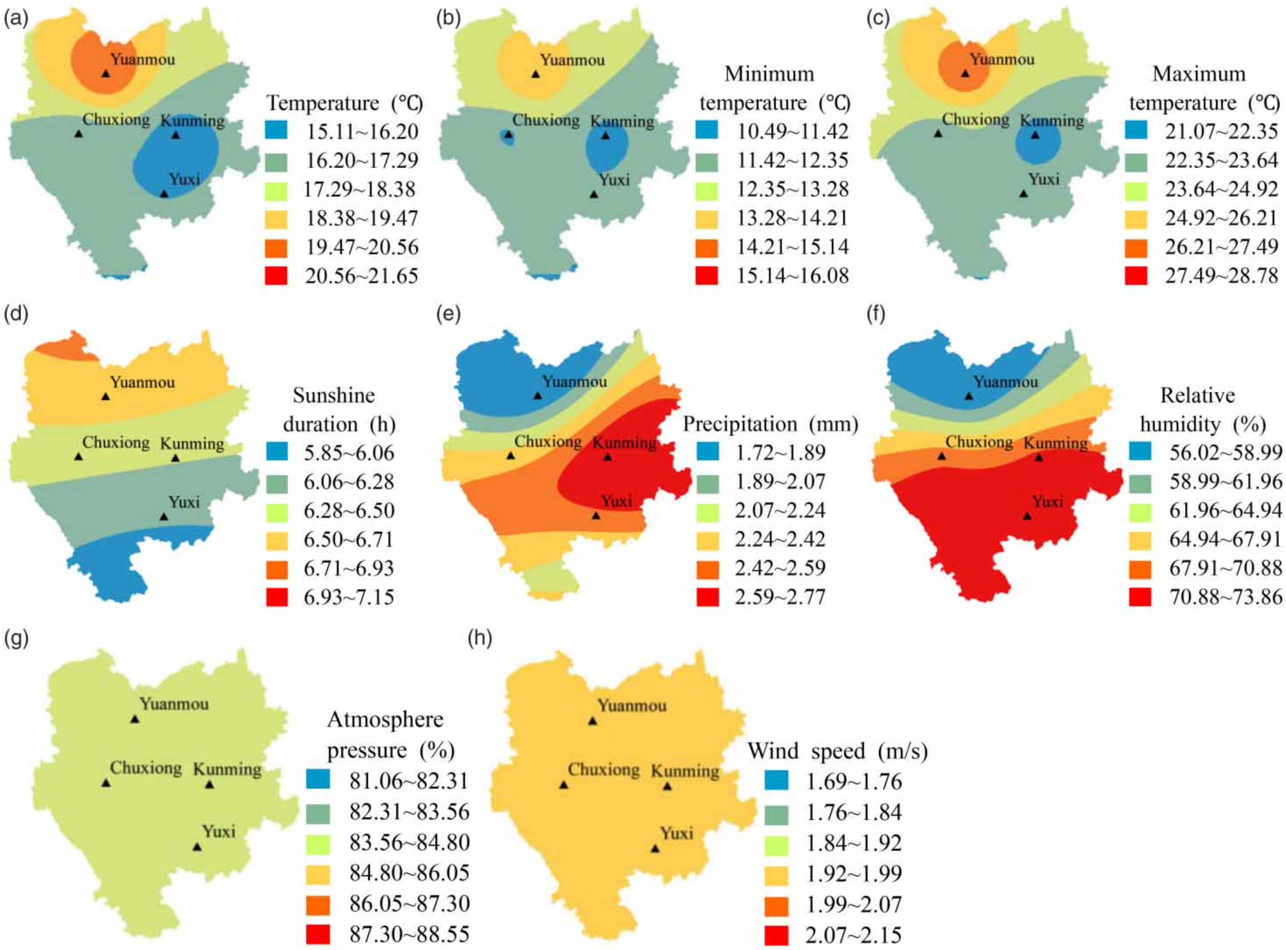

Figure 3 | Spatial distribution of the daily means for the principal climate characteristics in central Yunnan Province (based on 1956–2015 data): (a) mean temperature; (b) minimum temperature; (c) maximum temperature; (d) sunshine duration; (e) precipitation; (f) relative humidity; (g) atmosphere pressure; (h) wind speed.

precipitation as recommended by the United States Department of Agriculture (USDA) Soil Conservation Bureau (Smith 1992), which has proven to be effective (Tigkasa *et al.* 2016). The formula is as follows:

$$P_e = \begin{cases} (4.17 - 0.2P)/4.17 & P < 8.3\,\text{mm/day} \\ 4.17 + 0.1P & P \geq 8.3\,\text{mm/day} \end{cases} \quad (3)$$

where P is daily precipitation (mm/day).

The crop's ET_c is the water needed to support growth and development and incorporates the full crop production potential and the evaporation of all water (Snyder *et al.* 2012). It includes not only the water requirement to meet the growth of the crop itself but also includes the effects of farmland water and heat conditions on the demand for water (Liu *et al.* 2013). Flue-cured tobacco's water demand can be calculated by measuring the moisture using the water balance method and by assumptions involved in the comprehensive methods of climatology. The crop coefficient method was used to calculate the daily water demand of flue-cured tobacco (Wang *et al.* 2017). The formula is as follows:

$$ET_c = K_c ET_0 \quad (4)$$

where ET_0 is the reference crop evapotranspiration (mm/day) and K_c is the crop coefficient. The calculation method of ET_0 was adopted from the Penman–Monteith formula recommended by FAO 56 (Valiantzas 2013). This formula is based on the energy balance method and the theory of water vapor diffusion. The physiological characteristics and aerodynamic parameters of the crops are taken into account, which results in a good theoretical basis and a high computational accuracy (Allen *et al.* 1998; Fares *et al.* 2016). The formula is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_a - e_d)}{\Delta + \gamma(1+0.34U_2)} \quad (5)$$

where Δ is the saturation vapor pressure/temperature curve (kPa/°C), R_n is the net radiation from the canopy (MJ/(m^2 d)), G is the soil heat flux (MJ/(m^2 d)), γ is the wetting and drying constant (kPa/°C), T is the average daily temperature (°C), U_2 is the wind speed 2 m above the ground (m/s), e_a is the actual water vapor pressure (kPa), and e_d is the saturation vapor pressure (kPa). The values for Δ, R_n, G and U_2 can be calculated using observational data from the meteorological stations. The specific calculation procedure is shown in Table 2. K_c can be estimated by referencing related research results from China (Chen *et al.* 1995). The growth stage of flue-cured tobacco in the study area occurs from April to August every year. It can be divided into three periods: root-extending stage, vigorous growth stage and maturation stage. The three growth stages correspond to crop coefficient estimates of 0.7, 1 and 0.9 based on the average annual values. Combining Equations (4) and (5), and research based on daily meteorological data, the daily ET_c of flue-cured tobacco in central Yunnan Province was calculated, as were the statistics of water demand during the whole growth stage.

Future climate change scenarios

The summaries for policy makers (SPM) described in *Climate Change 2013: The Physical Science Basis* were released on 27 September, 2013 as part of the IPCC Fifth Assessment Report (AR5), which updated and supplemented the emissions scenarios published in the 2000 IPCC report (IPCC 2013). In the SPM, a new generation of scenarios was introduced. These scenarios were called Representative Concentration Pathways (RCPs), and included the RCP2.6, RCP4.5, RCP6 and RCP8.5 scenarios.

The RCP2.6 emission and concentration pathway represents the literature on mitigation scenarios, and its aim is to limit the increase in global mean temperature to 2 °C. This scenario is at the low end of the scenario literature values in terms of emissions and radiative forcing. It often shows negative emissions from energy use in the second half of the 21st century.

RCP4.5 is a scenario that attempts to predict the long-term, global emissions of greenhouse gases, short-lived species, and land-use/land-cover that will stabilize radiative

Table 2 | The names of each component in the Penman–Monteith equation and the formulae used to calculate them

Name	Formula	Units
Saturation vapor pressure/temperature curve	$\Delta = 4.098e_a/(T+237.3)^2$	kPa/°C
Actual water vapor pressure	$e_a = 0.611\times 10^{8.5T/(273+T)}$	kPa
Soil heat flux	$G = 0.1[T_i - (T_{i-1} + T_{i-2} + T_{i-3})/3]$	MJ/(m^2 d)
Constant of wetting and drying	$\gamma = 0.00163P/\lambda$	kPa/°C
Latent heat of vaporization of water	$\lambda = 2.501 - 0.002361T$	MJ/kg
Net radiation from the canopy	$R_n = R_{ns} - R_{nl}$	MJ/(m^2 d)
Net short-ware radiation	$R_s = (0.25 + 0.5n/N)R_a$ $R_{ns} = (1-0.23)R_s = 0.77R_s$	MJ/(m^2 d)
Net long-ware radiation	$R_{nl} = 2.45\times 10^{-9}(0.1+0.9n/N)$ $(0.34 - 0.14\sqrt{e_d})(T_{kx}^4 + T_{kn}^4)$	MJ/(m^2 d)
Theoretical total solar radiation	$R_a = 37.6d_r(w_r \sin\phi \sin\delta + \cos\phi\cos\delta\sin w_s)$	MJ/(m^2 d)
Sun-earth relative distance	$d_r = 1 + 0.033\cos(2\pi J/365)$	
Sun magnetic declination	$\delta = 0.409\sin(2\pi J/365 - 1.39)$	rad
Sunset hour angle	$\omega_s = \arccos(-\tan\phi\tan\delta)$	rad
Theoretical sunshine duration	$N = 24\omega_s/\pi$	h

forcing at 4.5 W/m^2 (approximately 650 ppm CO_2-equivalent) in the year 2100 without ever exceeding that value.

RCP6.0 describes a scenario for long-term, global emissions of greenhouse gases, short-lived species, and land-use/land-cover change that stabilizes radiative forcing at 6.0 W/m^2 in the year 2100 without exceeding that value in prior years.

RCP8.5 is a so-called 'baseline' scenario that does not include any specific climate mitigation target. The greenhouse gas emissions and concentrations in this scenario increase considerably over time, which leads to a radiative forcing of 8.5 W/m^2 by the end of the century.

The climate change projections predicted in this study for the mid-21st century (2046–2065) and the late-21st century (2081–2100) are based on these four scenarios (RCP2.6, RCP4.5, RCP6 and RCP8.5) (Shen & Wang 2013).

Principal component analysis

Principal component analyses are mainly used to analyze covariance matrices to reduce the data dimensionality while maintaining the worst contributions to the data set. Thus, under the premise of minimum information loss, the variables that affect the dependent variables are translated into one variable or several comprehensive variables. That is, the principal components are not correlated with each other (Hu *et al.* 2011; Dong *et al.* 2014).

The calculation process was as follows:

1. A matrix of standardized data metrics was obtained. In this article, the number of factors affecting irrigation demand was n, the number of years was m and the data matrix was X. X_{ij} represents the regions of the j numerical.

$$X = \begin{vmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{vmatrix} \tag{6}$$

2. The correlation coefficient matrix solution:

$$r_{ij} = \frac{\sum_{n=1}^{n} |(x_{ki} - \overline{x_i})||(x_{kj} - \overline{x_j})|}{\sqrt{\sum_{k=1}^{n} (x_{ki} - \overline{x_i})^2 \sum_{k=1}^{n} ((x_{kj} - \overline{x_j})^2)}} \tag{7}$$

where r_{ij} is the correlation coefficient between the ith index and jth from standardized data.

3. The eigenvalues and eigenvectors of the correlation coefficient matrix were solved, and the variance contribution and the cumulative contribution rates of the eigenvalues were calculated. The raw data information of the former q principal components were recorded when the eigenvalues were greater than 1 and the cumulative variance contribution rate was greater than 80%. The variance contribution rate was calculated as follows:

$$C = (c_1, c_2 \cdots, c_q) \tag{8}$$

4. The corresponding eigenvectors were standardized as follows:

$$A = \frac{\lfloor e_f - \min(e_f) \rfloor}{[\max(e_f) - \min(e_f)]} \tag{9}$$

where e is the characteristic vector, and $f \in [1, q]$.

5. The contribution rate of each index to the irrigation demand index was calculated as follows:

$$P = \frac{C.A^Q}{\sum_{i=1}^{q} Ci = (P_1, P_2, \cdots P_n)} \tag{10}$$

6. P was normalized as follows:

$$W = \frac{p_j}{\sum_{1}^{n} p_j = (w_1, w_2, \cdots w_n)} \tag{11}$$

where W_j is the weight of the jth index.

Data processing

Based on the ground surface meteorological data of the Kunming, Yuxi, Chuxiong and Yuanmou sites in Yunnan Province from 1956 to 2015, after using Excel to pretreat the data, the Penman–Monteith formula of FAO 56 and the crop coefficient method were used to calculate the daily crop water demand and daily water demand of flue-cured tobacco. Additionally, the *IR* values and the

IDI were obtained and used to analyze the temporal and spatial variation characteristics of the *IDI*, *IR* and ET_c. At the same time, using Matlab 2014 software to analyze the main components of crop *IDI* and the annual change in the meteorological factors, the effects of different meteorological factors on the *IDI* in Yunnan Province was analyzed.

RESULTS AND ANALYSIS

Temporal variation characteristics of *IDI* and ET_c in central Yunnan Province

In this study, the growth periods for flue-cured tobacco are defined by the historical transplant period for flue-cured tobacco in Yunnan province (Zheng *et al.* 2015). The growth stage of flue-cured tobacco in central Yunnan Province occurs from April 27th to August 24th, for a total of 120 d. The root-extending stage occurs from April 27th to May 26th, for a total of 30 d. The vigorous growth stage occurs from May 27th to June 25th, for a total of 30 d, and the maturation stage occurs from June 26th to August 24th, for a total of 60 d. Figure 4 shows the daily *IDI* and ET_c means and annual averages for flue-cured tobacco at each growth stage in central Yunnan Province. The daily mean *IDI* and ET_c values are the daily averages for each growth stage from 1956 to 2015.

Figure 4(a) shows the annual variation trend, daily mean value of the *IDI* and the ET_c during the root-extending stage of flue-cured tobacco in central Yunnan Province. In 2002, the *IDI* reached its lowest value in the study period, at 0.55, and in 1963, the *IDI* reached its highest value of 0.99. This was similar to the trend for the ET_c value because the lowest ET_c value (55.05 mm) was also in 2002, and the highest ET_c value (121.57 mm) was in 1963. The *IDI* daily mean minimum was 0.59 on May 25th, and the maximum value was 0.86 on April 27th in every year. The *IDI*'s mean value was 0.78 during the 30 d of the root-extending stage for flue-cured tobacco. This indicated that the root extending stage was an intense growth period for flue-cured tobacco and that natural precipitation could not meet the ET_c requirements for the growth stage. Thus, there was a need for artificial replenishment to meet the growth stage's water demand. The variations in ET_c and *IDI* were shown as the fluctuations in the decline, which was decreased to 2.58 mm/day and 0.62, respectively, from 3.23 mm/day and 0.86, respectively, from May 26 to April 27 during the growth stage.

Figure 4(b) shows the annual variation trend, daily mean value of the *IDI* and the ET_c during the vigorous growth stage of flue-cured tobacco in central Yunnan Province. The *IDI* experienced two great fluctuations during 1988–1994, with the maximum fluctuation reaching 47.56%. This indicated that in the study area, during this period, the transition between drought and flood was rapid. The ET_c showed an upward trend after 2012 and reached its maximum value for the past 60 years, which was 173.34 mm. This was consistent with the continuous drought pattern in central Yunnan Province. In recent years, based on the changes in the daily means of the two parameters, it was observed that the deviation between *IDI* and ET_c decreased gradually as the growth stage progressed. This was mainly due to the decreasing trends of both parameters during the vigorous growth stage. The declining trend of ET_c was greater, dropping to 2.92 from 3.75 mm/day by the whole growth stage. The decrease in amplitude was 22%. The ET_c of flue-cured tobacco crop gradually decreased as the growth duration increased. However, the *IR* declined over June 11, 12, and 13 in every year, and then recovered to the same level. Thus, the natural precipitation could not meet the growth and development of flue-cured tobacco in spite of the rainy season.

Figure 4(c) shows the annual variation trend, daily mean value of the *IDI* and the ET_c during the maturation stage of flue-cured tobacco in central Yunnan Province. The *IDI* had a small variation range between 1956 and 1981, with an extreme difference of 0.2, but in the years after that, the *IDI* fluctuated significantly and the extreme difference increased to 0.3. In contrast with the *IDI* of the three growth stages, as the flue-cured tobacco grew, the *IDI* also decreased, but the natural precipitation in central Yunnan Province increased gradually. The mean daily values of the ET_c in three growth stages were 2.99, 3.25 and 2.40 mm/day, respectively. Combined with the three growth period *IDI* curves, the cured tobacco plants in central Yunnan Province were greatly affected by precipitation. Although the precipitation began to increase, it was not

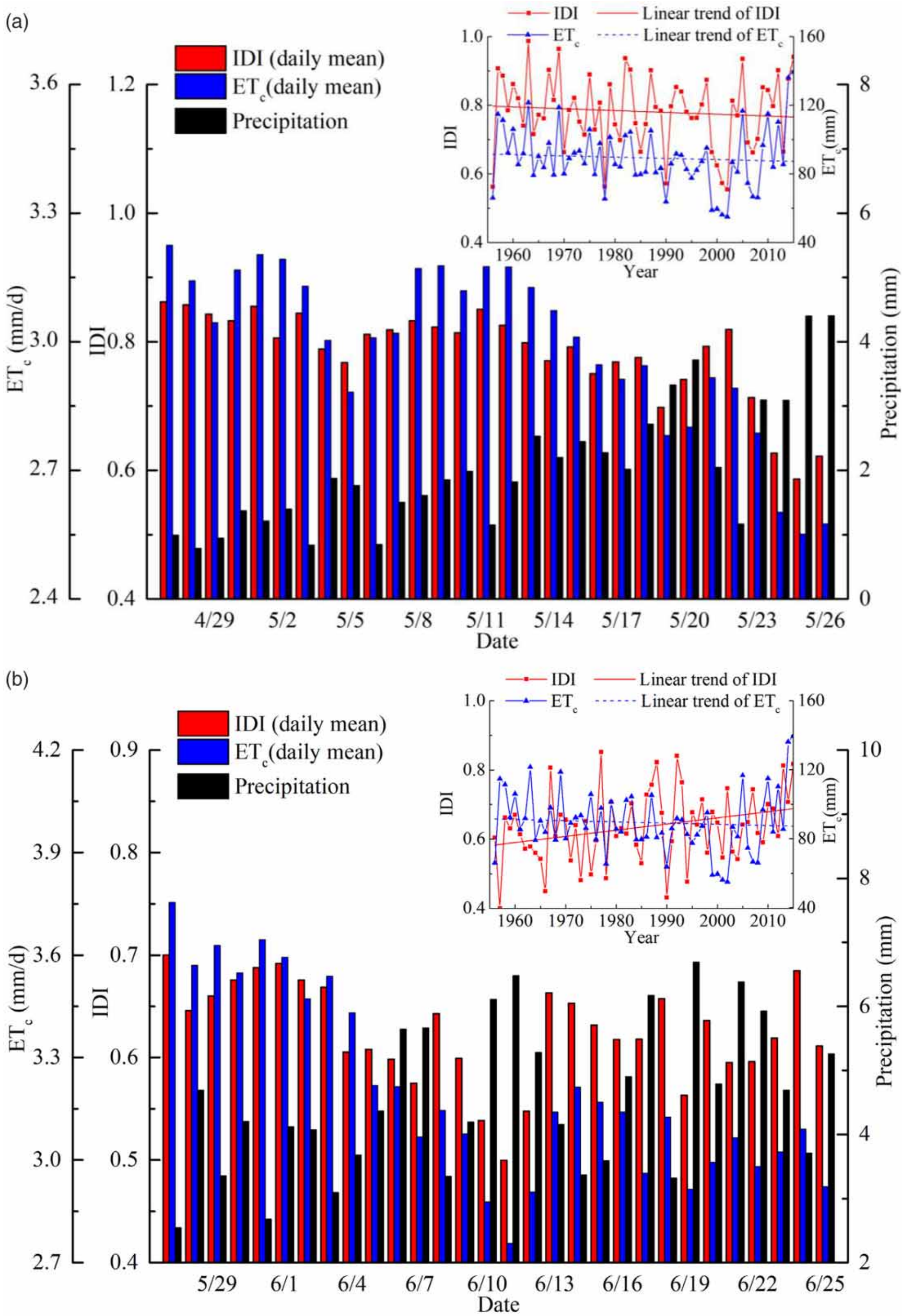

Figure 4 | Daily net irrigation requirement index (*IDI*), water requirements (ET_C) and precipitation means and the annual averages for flue-cured tobacco at every growth stage in central Yunnan Province, China: (a) root-extending stage; (b) vigorous growth stage; (c) mature stage; (d) whole growth period. (*continued*).

enough to satisfy the crop's requirements. Thus, it was necessary to strengthen the irrigation management practices during the growth of flue-cured tobacco. The average changes in the trends of *IDI* and ET_c showed that as the growth duration increased, the deviation from the trends decreased. The linear fitting of the ET_c value was −0.006, but the change in

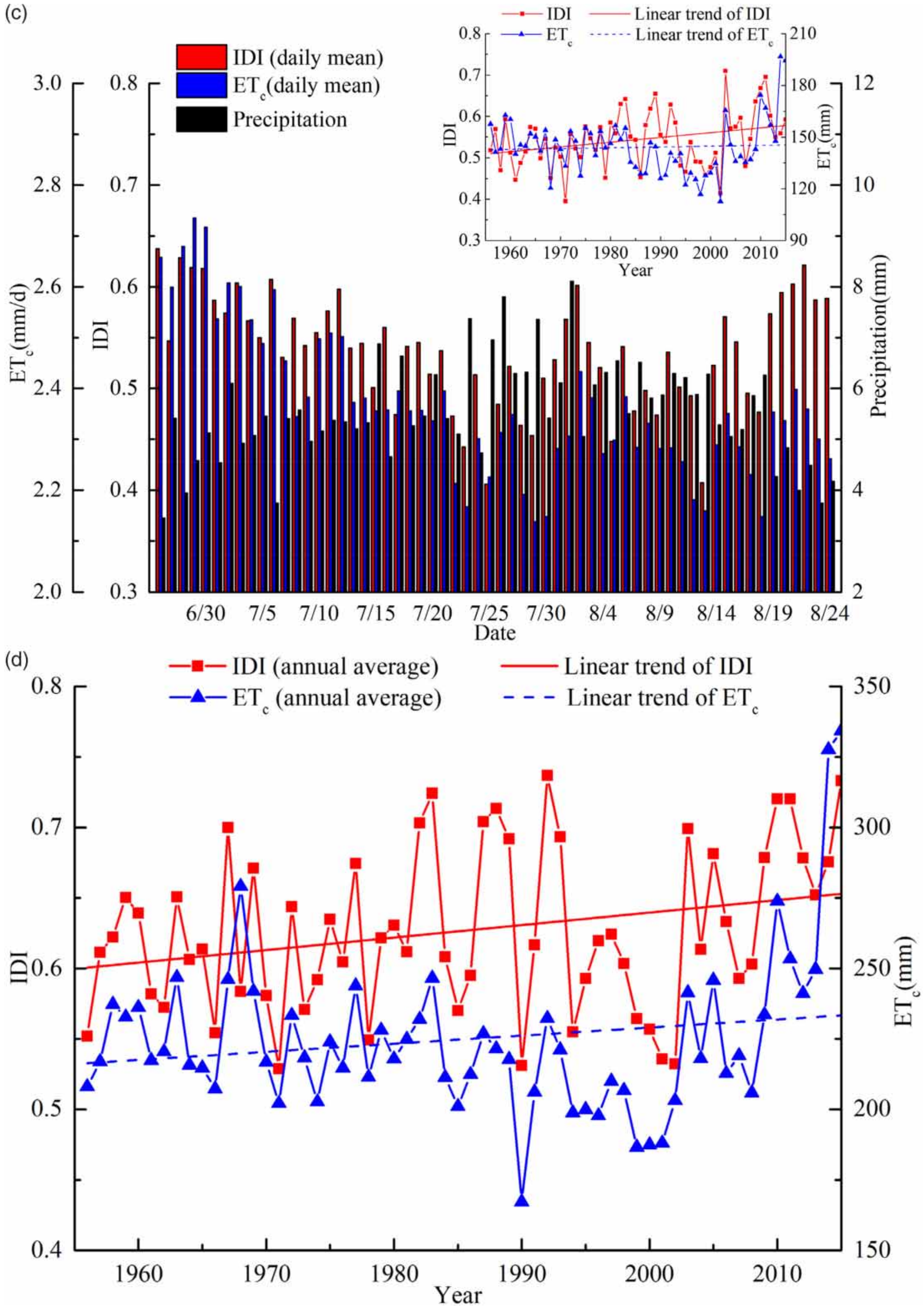

Figure 4 | Continued.

the *IDI* trend was relatively stable, decreasing to near 0.4 by July 25th and August 13th in every year.

Figure 4(d) shows the three growth periods of irrigation requirement indices during the flue-cured tobacco growth period in central Yunnan Province. From 1982 to 1993, the *IDI* fluctuated greatly, with an extreme value of 0.21, and the changes in drought and waterlogging during this short time seriously affected the growth of the cured tobacco crops. The annual variations of mean *IDI* and ET_c values in central Yunnan Province were 0.63 and 224.86 mm,

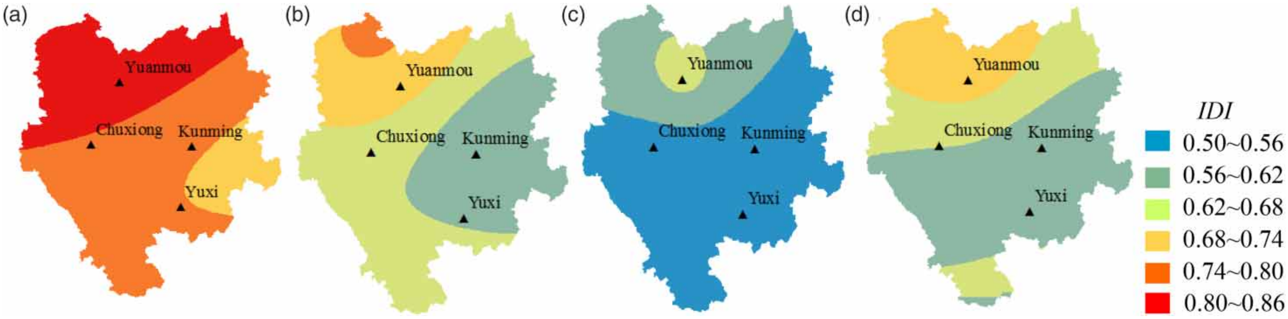

Figure 5 | Spatial distribution of the net irrigation requirement index (*IDI*) for flue-cured tobacco at each growth stage and the whole growth period in central Yunnan Province: (a) root-extending stage; (b) vigorous growth stage; (c) mature stage; and (d) whole growth period.

respectively. This showed that under normal precipitation conditions, cured tobacco during the growth period requires artificial irrigation, otherwise drought and water shortage conditions would occur.

Spatial distribution characteristics of the *IDI*, *IR* and ET_c of flue-cured tobacco in central Yunnan Province

Figures 5–7 show the spatial distribution characteristics of the *IDI*, *IR* and ET_c during each growth period over the whole growth period of flue-cured tobacco in central Yunnan Province. These values are all daily means for each growth stage from 1956 to 2015. The data for the four stations shown on the map were subjected to Kriging interpolations.

The maximum *IDI* value, 0.85, among the different growth stages of flue-cured tobacco occurred in the Yuanmou area during the root extending stage. The minimum value, 0.50, occurred in Kunming during the maturation stage. The whole growth period's *IDI* values ranged from

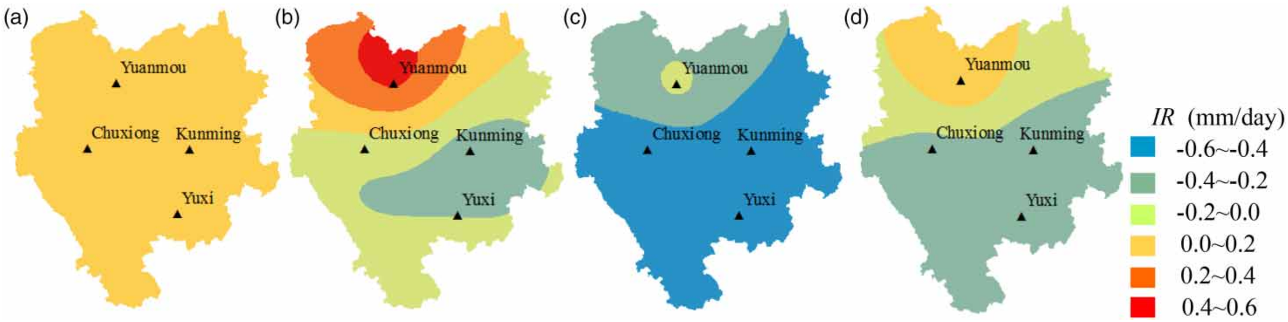

Figure 6 | Spatial distribution of the net irrigation water requirement (*IR*) for flue-cured tobacco at each growth stage and the whole growth period in central Yunnan Province: (a) root-extending stage; (b) vigorous growth stage; (c) mature stage; and (d) whole growth period.

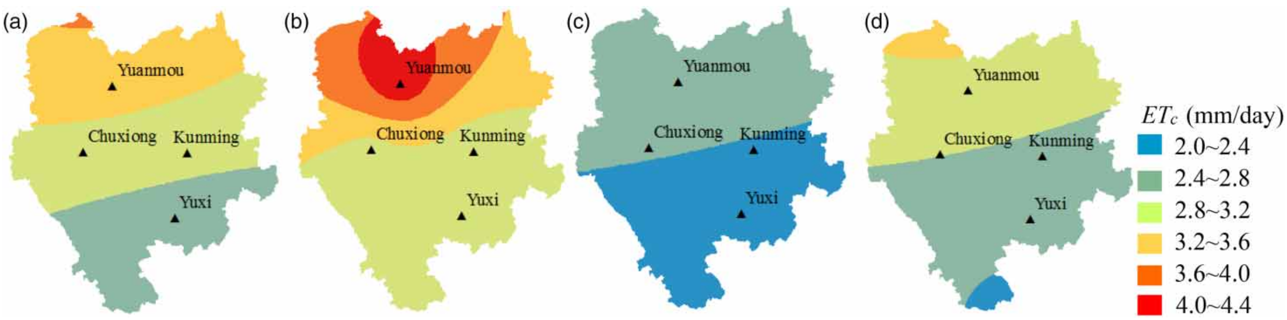

Figure 7 | Spatial distribution of water requirements (ET_C) for flue-cured tobacco at each growth stage and the whole growth period in central Yunnan Province: (a) root-extending stage; (b) vigorous growth stage; (c) mature stage; and (d) whole growth period.

0.58 to 0.71. Based on the changes in the *IDI*'s spatial distribution, shown in Figures 5(a)–5(c), the maximum *IDI* value of flue-cured tobacco occurred in the root-extending stage. The minimum *IDI* value of this period was 0.03 higher than the maximum values of the other two periods. This indicated that the root-extending stage requires more artificial irrigation water than the other growth stages. During the flue-cured tobacco's growth, the central Yunnan Province gradually enters the rainy season, with increasing precipitation, and the *IDI* value gradually decreased, but its minimum value was still greater than 0.5. The *IDI*'s spatial distribution during the whole growth period was concentrated between 0.56 and 0.68 in most regions of central Yunnan Province. The *IDI* distribution in each growth period was relatively larger in the Yuanmou area compared with other areas, while the *IDI* value was the smallest in the Kunming area.

The maximum *IR* value, 3.38 mm/day, among the different growth stages occurred during the root-extending stage in the Yuanmou area. The minimum *IR* value, −0.11 mm/day, occurred during the maturation stage in the Kunming area. The *IR* values during the vigorous growth stage differed greatly in the study area. The *IR* values in the Kunmming and Yuxi areas were small, ranging from 0.5 to 1.1 mm/day. In the Yuanmou area of northern central Yunnan Province, the values ranged from 2.9 to 3.5 mm/day. They showed a gradual increase with latitude owing to the Yuanmou area being a dry and hot valley region. The evaporation rate was rapid, and the average annual evaporation was 3,507.2 mm, which was 5.6 times the precipitation level. In the maturation stage of flue-cured tobacco, the *IR* values of the Chuxiong, Kunming and Yuxi areas were −0.1 to 0.5 mm/day, and the *IR* in each region had a small variation. The *IR* distribution of the whole growth period was between 0.5 and 2.3 mm/day.

ET_c indicates whether the water satisfies the growth and development of crops. The changes in the ET_c in the central Yunnan Province varied greatly during the growth period. The ET_c values increased gradually from south to north, and showed a zonal distribution, with minimum and maximum differences of 1.3 mm/day. The spatial distribution of the ET_c during the vigorous growth stage was significantly larger than in the other two growth periods. The maximum value was 4.37 mm/day in the Yuanmou area, while the maximum in the maturation stage was 3.1 mm/day. This indicated that the crops needed the largest amount of water over the long term and that the spatial distribution was complex. The ET_c distribution during the whole growth period of flue-cured tobacco showed differences between the north and south. The ET_c values in most regions in the study area had a distribution range of 2.4–3.2 mm/day. The mean value of the effective rainfall in the growth period was 1.69 mm/day.

Temporal and spatial ET_c variations in future climate change scenarios

The average annual ET_c data for the last 60 years (from 1956 to 2015), and the ET_c values for the flue-cured tobacco growth period at different stations in central Yunnan during the mid-21st century (2046–2065) and late-21st century (2081–2100) under the RCP2.6, RCP4.5, RCP6 and RCP8.5 scenarios were used to calculate the variation in water demand from the current value (average annual value over the last 60 years) and the variation rate (Table 3). For all the stations, the average water demand during the projected growth period between 2046 and 2065 differed from the current value by 3.27% to 10.87%, with the largest variation rate occurring at Chuxiong station under the RCP8.5 scenario. The average water demand during the growth period between 2081 and 2100 differed from the current value by 3.27% to 22.97%, with the largest variation rate occurring at Chuxiong station under the RCP8.5 scenario. Overall, the lowest variation in ET_c occurred under the RCP2.6 scenario, whereas the largest variation appeared under RCP8.5. This could be explained by the fact that the increased greenhouse gas concentration, radiative forcing and atmospheric temperature could lead to higher crop respiration and photosynthesis rates, which means that crops need to absorb more water to maintain their normal growth. This would lead to a larger ET_c.

The spatial variations shown in Figures 8 and 9 suggest that water demand during the growth period in central Yunnan will increase in both the mid- and late-21st century under all the scenarios, although the increase varies by station. The variations in water demand during the growth period in the mid- and late-21st century tend to increase with latitude. The largest variation occurs at Yuanmou station which is located in the north part of the study area

Table 3 | Changes in flue-cured tobacco water requirements (ET_c) for the whole growth period under the future scenarios in central Yunnan Province

		2046–2065			2081–2100		
Scenarios	**Station**	**ET_c (mm)**	**Variation (mm)**	**Rate (%)**	**ET_c (mm)**	**Variation (mm)**	**Rate (%)**
RCP2.6	Chuxiong	315.41	15.72	5.24	315.41	15.72	5.24
	Kunming	307.53	9.74	3.27	307.53	9.74	3.27
	Yuxi	304.05	10.02	3.41	304.05	10.02	3.41
	Yuanmou	455.63	19.77	4.54	455.63	19.77	4.54
	Mean	345.65	13.81	4.11	345.65	13.81	4.11
RCP4.5	Chuxiong	322.20	22.51	7.51	328.93	29.23	9.75
	Kunming	316.42	18.63	6.26	325.24	27.45	9.22
	Yuxi	311.67	17.64	6.00	319.23	25.19	8.57
	Yuanmou	464.44	28.58	6.56	473.16	37.31	8.56
	Mean	353.68	21.84	6.58	361.64	29.80	9.03
RCP6	Chuxiong	320.51	20.82	6.95	335.58	35.89	11.98
	Kunming	314.20	16.41	5.51	333.99	36.20	12.16
	Yuxi	309.77	15.74	5.35	326.71	32.68	11.11
	Yuanmou	462.25	26.39	6.05	481.80	45.94	10.54
	Mean	351.68	19.84	5.97	369.52	37.68	11.45
RCP8.5	Chuxiong	332.26	32.57	10.87	359.94	60.25	20.10
	Kunming	329.63	31.83	10.69	366.18	68.39	22.97
	Yuxi	322.98	28.95	9.84	354.14	60.11	20.44
	Yuanmou	477.49	41.63	9.55	513.36	77.50	17.78
	Mean	365.59	33.75	10.24	398.40	66.56	20.32

where the variations in water demand compared to the current value are 41.63 and 77.50 mm for the periods 2046–2065 and 2081–2100, respectively.

Principal component analysis of the impact that meteorological factors had on the *IDI* values of flue-cured tobacco

To determine the contributions of meteorological factors to the *IR* of flue-cured tobacco, using SPSS software to analyze the data, the eigenvalue table of the sample covariance matrix was obtained. The results are shown in Table 4. In general, if the principal component of the characteristic root is greater than 1, and the cumulative variance contribution rate is greater than 80%, then the analysis of the principal component was suitable. Table 4 shows that the characteristic roots of the first three principal components were greater than 1, and the cumulative variance contribution rate was 85.17%, which was greater than 80%. The index contribution rate was also greater.

Tables 5 and 6 show the principal component analysis of nine meteorological factors in central Yunnan Province.

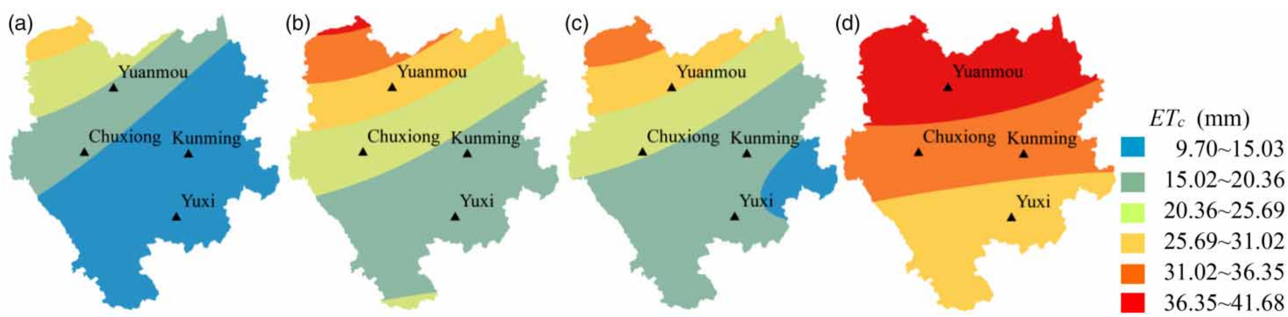

Figure 8 | Spatial distribution of the flue-cured tobacco water requirements (ET_c) for the whole growth period under the different climate change scenarios in central Yunnan Province between 2046 and 2065: (a) RCP2.6; (b) RCP4.5; (c) RCP6; and (d) RCP8.5.

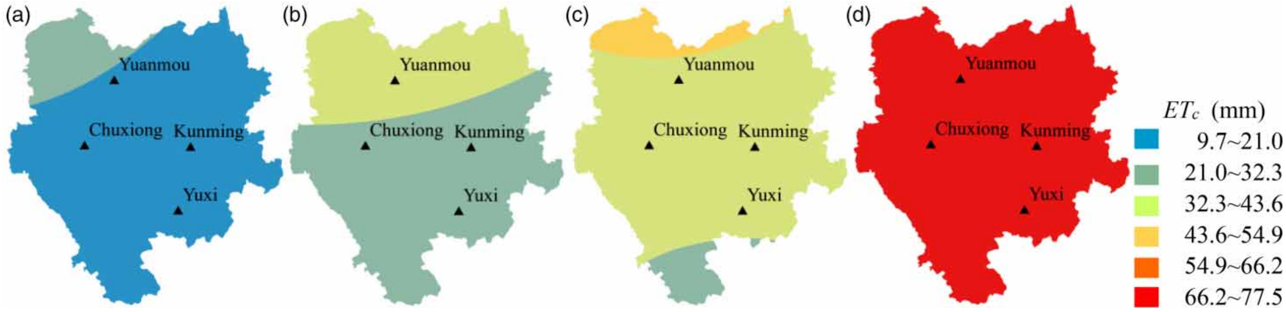

Figure 9 | Spatial distribution of the flue-cured tobacco water requirements (ET_c) for the whole growth period under the different climate change scenarios in central Yunnan Province between 2081 and 2100: (a) RCP2.6; (b) RCP4.5; (c) RCP6; and (d) RCP8.5.

Table 5 shows the coefficients for each meteorological factor in the principal component analysis model. It also shows the weights of each meteorological factor to the *IDI*. In Table 6, the maximum meteorological factor affecting the crop irrigation demand index was precipitation, with an index weight of 0.74. This indicated that the magnitude of rainfall had the greatest influence on irrigation in the research area. The weight of humidity was 0.64, which was the second largest of the indicators. The influence of pressure on the *IDI* was 0.60, which indicated that the pressure effect on the

Table 4 | Eigenvalues of the covariance matrix

Principal component	Eigenvalue	Variance contribution rate (%)	Cumulative variance contribution rate (%)
1	4.47	50.62	50.62
2	1.49	18.58	69.20
3	1.17	15.97	85.17
4	0.86	6.50	91.66
5	0.61	5.75	97.41
6	0.29	1.73	99.14
7	0.09	0.46	99.60
8	0.03	0.38	99.98
9	0.00	0.02	100.00

Table 6 | Index weights for the meteorological factors

Meteorological factors	The coefficients in the composite scoring model	Index weight
Precipitation	0.38	0.74
Air pressure	0.30	0.60
Wind speed	–0.33	–0.66
Temperature	–0.33	–0.66
Moisture	0.22	0.43
Maximum temperature	–0.18	–0.36
Relative humidity	0.33	0.64
Minimum temperature	0.18	0.34
Sunshine duration	–0.05	–0.09

Table 5 | Coefficients of the meteorological factors used in the comprehensive scoring model

		The first principal component	The second principal component	The third principal component
Coefficients in linear combinations	Variance of principal component	50.62	18.58	15.97
	Precipitation	0.74	–0.05	–0.27
	Air pressure	0.26	0.32	0.40
	Wind speed	–0.34	–0.46	–0.15
	Temperature	–0.56	0.21	–0.24
	Moisture	0.37	0.04	–0.04
	Maximum temperature	–0.41	0.33	–0.07
	Relative humidity	0.53	–0.16	0.25
	Minimum temperature	0.17	0.35	0.00
	Sunshine duration	–0.23	–0.20	0.71

irrigation demand index was also great. When the weight of the index is greater than 0, the meteorological factor was positively correlated with *IDI*. The greater the index weight, the less water the crops required. The index weight of wind speed and temperature on *IDI* were −0.66, which were the largest of the negatively correlated meteorological factors. The second greatest negatively correlated meteorological factor was the daily maximum temperature, with an index weight of −0.36. The greater the index weights of meteorological factors that were negatively correlated with the *IDI*, the more beneficial the meteorological factor to drought relief. Thus, the meteorological factors in central Yunnan Province are positively correlated with the *IR* of flue-cured tobacco, and the order of the positive effects is as follows: precipitation > relative humidity > air pressure > moisture > daily minimum temperature. The order of the negative effects is as follows: wind speed > temperature > daily maximum temperature > sunshine duration. Owing to the mutual influences and restrictions between meteorological factors, the *IDI* was not only affected by single meteorological factors, but also by meteorological factor interactions.

DISCUSSION

The factors influencing the *IDI* are complicated. Based on factors such as planting area, cropping system, altitude and growing region, Gu *et al.* (2010) found that precipitation was the main driving factor of *IR*. This was consistent with our results which found that after 2009, the precipitation in central Yunnan Province decreased. The precipitation amounts from 2009 to 2013 were 471.08, 374.18, 338.30, 393.45 and 420.18 mm, which were significantly lower than the average level of 530.55 mm during the study period. From 2009 to 2013, the *IR* and ET_c values of flue-cured tobacco showed an increasing trend. This was consistent with Ren *et al.* (2014) and other studies of arid climate changes in Yunnan that concluded that 2009/2010 was extremely arid and 2011/2012 was a heavy drought period.

The spatial analyses of ET_c, *IR* and *IDI* indicated that the changes in the three indices were consistent with the change in latitude, with the index increasing along with the latitude. The climate in central Yunnan Province is extensive, including middle subtropical, north subtropical and dry hot valley zones. In the context of global climate change, precipitation decreased as the latitude increased, and the evaporation on flue-cured tobacco occurred gradually. In the dry-hot valleys, such as the Yuanmou region, the special topography and underlying surface cover changed crop transpiration, with evaporation of precipitation generally having a higher rate relative to other areas, and this had important effects on the surrounding areas of flue-cured tobacco planting. This corroborated the research of Zheng *et al.* (2015) on the temporal and spatial characteristics of ET_c and *IDI* of flue-cured tobacco in Yunnan. Additionally, the change of altitude in central Yunnan Province was greater, which affects the evapotranspiration of crops. However, the ET_c of flue-cured tobacco in the same growth period did not show the influence of altitude. This was contrary to the study of Xu *et al.* (2005). The specific reasons for the study of evapotranspiration require further studies.

At present, there are few studies on flue-cured tobacco that investigate *IR* in Yunnan Province. Most research focused on the flue-cured tobacco planting area in Henan Province. Based on the *IDI*, we studied the water demand changes of flue-cured tobacco during different growing periods and climatic changes in central Yunnan Province. By combining the drought index, *IDI* and *IR* of flue-cured tobacco, the planting drought level of flue-cured tobacco was investigated in central Yunnan Province, which could provide theoretical science-based support for irrigation water use for flue-cured tobacco during different growth stages.

Precipitation is the major meteorological factor that is positively correlated with the *IDI* for flue-cured tobacco during its growth period. In contrast, temperature and wind speed are negatively correlated with *IDI*. Evapotranspiration and respiration due to flue-cured tobacco both increase with temperature, which means that the tobacco crop grows more vigorously. However, this leads to an increase in crop ET_c. Wind speed and sunshine-related factors could also affect the relative humidity of the air, which will affect the evaporation rate at the leaf surface. The diurnal temperature variation affects organic matter accumulation by crops. Furthermore, precipitation plays an important role in maintaining the environmental balance for crop growth. For example, enhanced precipitation can result in an increase in air humidity and soil moisture, which will facilitate nutrient uptake by crops. Future studies should quantitatively analyze the influences of meteorological factors on the yield and quality of flue-cured tobacco so that the most suitable climate environment for flue-cured tobacco crops in central Yunnan can be identified. This will improve crop management and water resources utilization in the central Yunnan region.

We have also identified the changes in flue-cured tobacco ET_c over the past 60 years and estimated the changes for two future periods. The ET_c and soil moisture at different stages of the growth period, future meteorological data and weightings for the influence of different meteorological factors on *IDI* were used to produce a water requirement model that dynamically analyzes the optimal amounts of irrigation water needed at different growth stages. Traditional crop irrigation projection models rely heavily on climate generators to obtain hydrological estimates for future years, which basically means that the historical pattern is used to develop future irrigation strategies. There are two disadvantages to the traditional methods. The first is that the irrigation level projection is based on the annual scale, and the second is that the projected data is not very useful in practice. Therefore, in order to improve the accuracy of the projection model, it is necessary to assign a weight to each meteorological factor. This could lead to increased water savings in agriculture and improve irrigation efficiency.

CONCLUSIONS

In this paper, a variety of methods were used to study the ET_c of flue-cured tobacco in central Yunnan Province. The results suggested that the following conclusions can be made:

1. During the period, 1956–2015, the *IDI* value decreased with time during the flue-cured tobacco growth period in central Yunnan Province. The *IDI* value at the maturation stage was 30.77% lower than at the root-extending stage. This was because it is the rainy season in central Yunnan Province during the maturation stage. The increased precipitation and decreased sunshine hours reduce the *IDI*. However, precipitation during the maturation stage does not meet the growth needs of the crop. In addition, the ET_c values at the root-extending stage and the maturation stage tend to decrease by year, whereas an opposite ET_c trend occurs during the fast-growing stage. In general, the ET_c over the whole growth period has constantly increased since 2002, although there were some fluctuations. It reached a maximum value over the past 60 years in 2015.
2. The ET_c trend varies at different stages of the growth period. The ET_c remains relatively stable during the root-extending stage and starts to drop from May 31st. During the fast-growing stage and the maturation stage, the temporal variation in ET_c follows a V-shaped curve, with the minimum value occurring on June 11th and July 29th, respectively. The temporal variation in the *IDI* over the whole growth period is quite stable with only a slight decrease over a couple of days before it returns to its original level. The average daily *IDI* and ET_c, values during the whole growth period, tend to deviate less from the trend line over time.
3. The spatial analysis showed that ET_c, *IR* and *IDI* all tend to increase from the south to the north with all the maximum values occurring near the Yuanmou station. This trend is particularly apparent during the fast-growing stage, and indicates that the climate in the hot and dry valleys of Yuanmou has a considerable impact on the flue-cured tobacco ET_c over the whole growth period. Furthermore, the spatial variations in ET_c, *IR*, and *IDI* during the fast-growing stage are more apparent than in the other two stages, which demonstrates a more obvious regional distribution. This is mainly caused by the Yuxi and Yuanmou stations, which have unique regional microclimates.
4. The average ET_c for the predicted growth periods between 2046 and 2065 differs from the current value by 3.27% to 10.87% with the largest variation rate occurring at Chuxiong station under the RCP8.5 scenario. The average ET_c for the predicted growth periods between 2081 and 2100 differs from the current value by 3.27% to 22.97% with the largest variation rate occurring at Chuxiong station under the RCP8.5 scenario. The variations in ET_c for the predicted growth periods in the mid- and late-21st century tend to increase with latitude.

5. In the principal component analysis of the meteorological factors for the *IDI* of flue-cured tobacco, the greatest positive correlation was between precipitation and *IDI*, and the greatest negative correlations to *IDI* were for wind speed and temperature. The order of positive effects was as follows: precipitation > relative humidity > air pressure > moisture > daily minimum temperature. The order of negative effects was as follows: wind speed > temperature > daily maximum temperature > sunshine duration.

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