Chin. Geogra. Sci. 2016 Vol. 26 No. 5 pp. 687–702
doi: 10.1007/s11769-016-0820-3

Springer Science Press
www.springerlink.com/content/1002-0063

Variation of Thornthwaite Moisture Index in Hengduan Mountains, China

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Abstract: The Thornthwaite moisture index, an index of the supply of water (precipitation) in an area relative to the climatic demand for water (potential evapotranspiration), was used to examine the spatial and temporal variation of drought and to verify the influence of environmental factors on the drought in the Hengduan Mountains, China. Results indicate that the Thornthwaite moisture index in the Hengduan Mountains had been increasing since 1960 with a rate of 0.1938/yr. Annual Thornthwaite moisture index in Hengduan Mountains was between –97.47 and 67.43 and the spatial heterogeneity was obvious in different seasons. Thornthwaite moisture index was high in the north and low in the south, and the monsoon rainfall had a significant impact on its spatial distribution. The tendency rate of Thornthwaite moisture index variation varied in different seasons, and the increasing trends in spring were greater than that in summer and autumn. However, the Thornthwaite moisture index decreased in winter. Thornthwaite moisture index increased greatly in the north and there was a small growth in the south of Hengduan Mountains. The increase of precipitation and decrease of evaporation lead to the increase of Thornthwaite moisture index. Thornthwaite moisture index has strong correlation with vegetation coverage. It can be seen that the correlation between Normalized Difference Vegetation Index (NDVI) and Thornthwaite moisture index was positive in spring and summer, but negative in autumn and winter. Correlation between Thornthwaite moisture index and relative soil relative moisture content was positive in spring, summer and autumn, but negative in winter. The typical mountainous terrain affect the distribution of temperature, precipitation, wind speed and other meteorological factors in this region, and then affect the spatial distribution of Thornthwaite moisture index. The unique ridge-gorge terrain caused the continuity of water-heat distribution from the north to south, and the water-heat was stronger than that from the east to west part, and thus determined the spatial distribution of Thornthwaite moisture index. The drought in the Hengduan Mountains area is mainly due to the unstable South Asian monsoon rainfall time.

Keywords: Thornthwaite moisture index; Normalized Difference Vegetation Index (NDVI); Kriging interpolation; Hengduan Mountains

Citation: Zhu Guofeng, Qin Dahe, Tong Huali, Liu Yuanfeng, Li Jiafang, Chen Dongdong, Wang Kai, Hu Pengfei, 2016. Variation of Thornthwaite moisture index in Hengduan Mountains, China. *Chinese Geographical Science*, 26(5): 687–702. doi: 10.1007/s11769-016-0820-3

1 Introduction

Droughts is a common, widespread natural phenomenon. Its impacts varie with rainfall intensity and spatial distribution (Wilhite, 2000; Kallis, 2008). Due to droughts is fundamentally driven by precipitation deficits, drought-monitoring data are typically reported and broadly applied (Choi *et al*., 2013). With global warm-

Received date: 2015-08-25; accepted date: 2015-11-02

Foundation item: Under the auspices of Chinese Postdoctoral Science Foundation (No. 2015M570864), Open-ended Fund of State Key Laboratory of Cryosphere Sciences, Chinese Academy of Sciences (No. SKLCS-OP-2014-11), Northwest Normal University Young Teachers Scientific Research Ability Promotion Plan (No. NWNU-LKQN-13-10), National Natural Science Foundation of China (No. 41273010, 41271133), Major National Research Projects of China (No. 2013CBA01808)

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ing, a change of moisture conditions was predicted that drought would sustain existing in some areas (Wang, 2005; Paltineanu *et al*., 2007; Seager *et al*., 2007; Gao and Giorgi, 2008; Tabari and Talaee, 2013). In general, drought can be defined as a period of abnormally dry weather, which further results in a change of vegetation cover condition (Heim, 2002; Tabari and Talaee, 2013). Over the last decades, the frequency and intensity of droughts have increased (Hulme and Kelly, 1993; Mccarthy *et al*., 2001), and there has been an obvious drying trend over many parts of the world, which has been suffering from more serious water crisis (Dai *et al*., 2004; Ghulam *et al*., 2008). The proportion of land surface of extreme drought is projected to increase in the future, particularly in continental interiors during summer (Change and Water, 2008). However, drought is a complicated issue subject to evapo-transpiration, temperature, rainfall, available soil moisture content and ground water. In recent years, remote sensing technology is applied more widely to the study of regional drought, but because of complicated terrain in Hengduan Mountain area, the remote sensing data have low accuracy.

There is a long history of evaluating the moisture conditions through the ratio of precipitation over temperature or evapotranspiration (Thornthwaite, 1948; UNESCO, 1979; Agnew, 1993; Vicente-Serrano *et al*., 2010; Gobena and Gan, 2013). Among many drought indices currently produced, some have had a long history within the drought research (Mendicino *et al*., 2008), such as the Palmer moisture anomaly index (Z-index) and the Palmer Drought Severity Index (Palmer, 1965). Satellite remote sensing provides an alternative approach to monitor drought over large areas. In contrast to the standard precipitation-driven drought indices, remotely sensed drought indices have a shorter period of records. The Thornthwaite moisture index (Thornthwaite and Mather, 1955) is an indicator of water supply related to the demand under prevailing climatic conditions (McCabe and Wolock, 1992). From the index, it can be seen that it is a measure to determine water requirements periods and quantities of water surplus, as well as water deficit by comparing precipitation and potential evapotranspiration. The water deficiency represents the amount that the precipitation fails to meet the demands of potential evapotranspiration (Rakhecha and Dhar, 1975). The index can be applied for climate classification, water management, environmental studies, and agricultural (Dourado-Neto *et al*., 2010). In the climate change and water resources studies, the Thornthwaite moisture index has also been used. Abdulla (2008) investigated the magnitude of water deficiency in the arid land in Iraq using the moisture deficit index (MDI). Moisture deficit index ranges from −80 to 94 in Baghdad and Bassra stations. Grundstein (2009) studied climate variability over the continental United States by Thornthwaite moisture index. The climate of Iran is generally becoming warmer and drier which shows remarkable variability and change (Tabari and Talaee, 2011a; 2011b; Some′e *et al*., 2012; Soltani *et al*., 2012).

The climate of the Hengduan Mountains is generally becoming warmer which shows remarkable variability and change (Zhu *et al*., 2012; 2013). Because of diverse terrain, climate systems, regional wet and dry conditions, it is necessary to find a simple, intuitive way to assess drought conditions in different regions. In this paper we discuss a simple, intuitive way to assess drought. This information can be obtained from National Meteorology Bureau of China, once temperature, precipitation, sunshine, wind speed, vapour pressure, relative humidity can be known by the moisture index calculation. This means the index could be quickly and easily applied to assess climate moisture content in region of interest.

We present a study of the moisture conditions in the Hengduan Mountains during 1960–2012 with the Kriging interpolation method. The main objective of this paper is: a) to characterize the spatial and temporal variability of the Thornthwaite moisture index in Hengduan Mountains; b) to identify the influence factors of Thornthwaite moisture index on the spatial and temporal variability.

2 Materials and Method

2.1 Study area

The Hengduan Mountains lies in the southeastern part of the Qinghai-Tibet Plateau (24°40′–34°00′N, 96°20′–104°30′E), with an area of 500 000 km^2 (Fig. 1) (Li and Su, 1996; Zhu *et al*., 2012; 2013). The region consists of a series of mountain and rivers running from north to south and Minya konka, which is located in the central area and is the highest (7756 m) of the Hengduan Mountains. There are 28 higher peaks with the elevations of above 6000 m, and the mountainous area above 5000 m accounts for 25% of the Hengduan Mountains. The Hengduan Mountains is also a world-famous longitudinal range-gorge region. Which is characterized by north-south rivers and mountains aligned from west to east, it is an obstruction to the eastern Asia monsoon and a thorough to the southern Asia monsoon. The topography declines from northwest to southeast. The region includes subtropical and plateau temperate climate zones, and the climate is vertically variable due to the complex mountainous topography. The soil and biodiversity are remarkable, attributed to the monsoonal climate and the larger vertical gradient. It is a typical monsoonal climate region, which is controlled by the South Asia monsoon and the East Asia monsoon; in addition, it is also influenced by the Qinghai-Tibet Plateau monsoon and the westerlies. Correspondingly, moisture transfer can be also characterized by the obvious seasonal change. Mainly the moisture comes from the westerlies in winter and spring. In summer, the moist maritime air originates from the Bay of Bengal and the South China Sea, and is mainly obtained from the western Pacific Ocean in autumn. Monsoonal circulation in Hengduan Mountains expands to 40°N in the beginning of August, but withdraws to 30°N in October. Monsoon strengthens or weakens, advances or retreats, often results in the occurrence of flood or drought. The winter monsoon period is from December to April. May to October is the summer monsoon period, precipitation accounts for about 90% of the annual total. Owing to the topography, there is abundant precipitation and low temperature in the higher altitude area. There are 1929 glaciers with an area of 1912.01 km^2 and the elevation scope ranged from 4620 m to 5440 m (Pu, 1994). Drought is the major natural disaster that has affected Hengduan Mountains, possibly attributed to the redistribution of surface water budget as a result of global and regional climate change.

Drought is the main meteorological disasters in Hengduan Mountains. According to the records, there was an increasing trend of drought disasters showed in recent years. The agricultural effects on drought for drought-induced areas, drought-affected areas, lost harvest areas and comprehensive loss rate increased in the last 60 years in Hengduan Mountains. The drought conditions in large farming areas of Hengduan Mountains, which were frequently hit by serious droughts. The average annual comprehensive loss rate accounted for 3.9% in Hengduan Mountains, and increased in recent years. Drought tolerance is related to regional climate

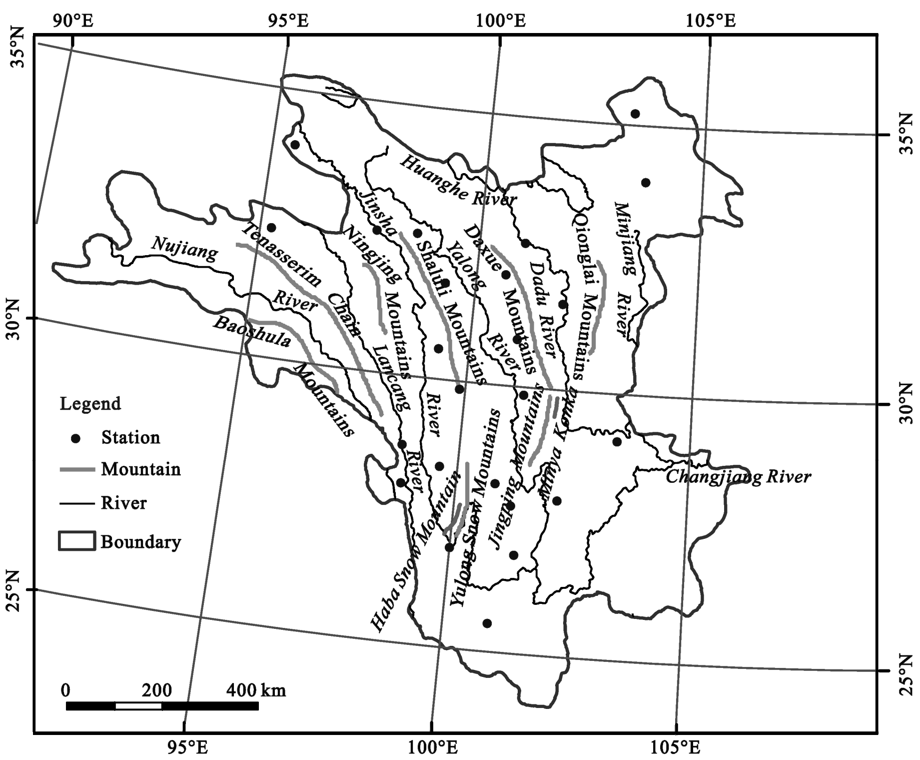

Fig. 1 Location of study area and distribution of meteorological stations

change effects, such as temperature, precipitation, moisture, and vegetation coverage (Han *et al*., 2014).

2.2 Data

The historical climatic data were obtained from 24 meteorological stations in the study area (Fig. 1, Table 1), which were originally provided by National Meteorology Bureau of China (http://www.nmic.gov.cn/). The observed meteorological data included daily precipitation, air temperature (maximum, minimum, and average), daily sunshine duration, average wind speed and relative humidity. The Penmane-Monteith model modified by Food and Agriculture Organization of the United Nations (FAO) is usually applied for estimating potential evapotranspiration (Thornthwaite and Mather, 1951; Jensen *et al*., 1990; Liu *et al*., 2005; Jia *et al*., 2009; Zhu *et al*., 2012). Potential evapotranspiration during 1960–2012 in the study area was calculated with the daily data of average temperature, maximum temperature, minimum temperature, average relative humidity, wind speed and sunshine hours. Data of 16 agrometeorological stations in the Hengduan Mountains were obtained from the Meteorology Center, National Meteorological Administration of the China (http://www.nmic.gov.cn/). The measured values of soil relative moisture were used to analyze the relationship of Thornthwaite moisture index and soil moisture. The observation depths of soil were 10, 20 and 50 cm, and the observation dates were the 8th, 18th and 28th of each month. When different depth soil layer were drilled and taken as samples, these samples were packed in an aluminum box, and then baked in an oven for 12 h continuously at a temperature of 105℃. The soil moisture content and field capacity in the sampling point were measured, and the soil relative moisture content can be calculated as:

$$R = M_w / S_w \times 100\% \qquad (1)$$

where R is the soil relative moisture content; M_w is the soil water content (%) and S_w is the field capacity (%).

Each year was divided into four seasons: spring, from March to May; summer, from June to August; autumn, from September to November; winter, from December to February of next year. The sampling period was divided into two stages, i.e., monsoon season (Jun., Jul., Aug., Sept.), and non-monsoon season (other months). Furthermore, the non-monsoon season was divided into pre-monsoon (Mar., Apr., May) and post-monsoon (Oct., Nov., Dec., Jan., Feb.) seasons.

Data of National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR) NDVI (1992–1998) and Systeme Probatoire d'Observation de la Terre (SPOT) Vegetation (SPOTVEG) NDVI (1999–2010) in the Hengduan Mountains were obtained from the Environmental and Ecological science Data center for west china (http://westdc.westgis.ac.cn) and Centered Traitement d'Images VEGETATION (CTIV) (http://www.spot-vegetation.com). The NOAA/AVHRR NDVI had atmospheric and radiometric correction by Global Inventory Monitoring and Modeling Studies (GIMMS): the spatial resolution was 8 km and temporal resolution was 15 d. The SPOTVEG NDVI underwent atmospheric, radiometric

Table 1 Information of meteorological stations in Hengduan Mountains

Meteorological station	Longitude (°)	Latitude (°)	Elevation (m)	Meteorological station	Longitude (°)	Latitude (°)	Elevation (m)
Chuxiong	101.30	25.02	1013.3	Kangding	101.58	30.03	1015.8
Dali	100.11	25.70	1001.1	Litang	100.16	30.00	1001.6
Zayü	97.50	28.70	2800.0	Barkam	102.14	31.54	1021.4
Dawu	101.07	30.59	1010.7	Muli	101.16	27.56	1011.6
Daocheng	100.18	29.03	1001.8	Zoigê	102.38	34.05	1023.8
Daoshan	99.11	25.07	991.1	Sêrxü	98.06	32.59	980.6
Dêgê	98.35	31.48	983.5	Songpan	102.21	31.00	1022.1
Dêqên	98.55	28.29	985.5	Xichang	102.16	27.54	1021.6
Dingqing	95.36	31.25	3873.1	Xiaojin	102.21	31.00	1022.1
Garzê	100.00	31.37	1000.0	Xinlong	100.19	30.56	1001.9
Gongshan	98.40	27.45	984.0	Yuexi	102.31	28.39	1023.1
Huaping	101.16	26.38	1011.6	Jiulong	101.30	29.00	1013.0

and geometric correction: the spatial resolution was 1 km and temporal resolution was 10 d.

The Mann-Kendall trend test (Mann, 1945; Kendall and Gibbons, 1990; Hamed, 2009) was applied to analyze the soil and meteorological data. It is one of the most widely used nonparametric tests for detecting trends in time series, which can also be used to evaluate whether there is a significant discontinuity and change of the data collected.

2.3 Methods

2.3.1 Determination of Thornthwaite moisture index

The Thornthwaite moisture index used in this study was devised by Thornthwaite and Mather (1955) and modified by Willmott and Feddema (1992) (Table 2). It is a dimensionless index that is bounded from −1 to 1. Positive values indicate a humid climate with a water surplus, whereas negative values indicate an arid climate with a water deficit (McCabe and Wolock, 1992). The index were used to analyze the interaction between energy and surface moisture and the breaks in climatological and hydrological components coincide with breaks in vegetation regions (Jewell and Mitchell, 2009; Keim, 2010; Elguindi *et al*., 2014). The calculation method of Thornthwaite moisture index is given by Equation (2).

$$MI = \begin{cases} (P/PET-1), \; P < PET \\ (1-PET/P), \; P > PET \\ 0, \; P = PET = 0 \end{cases} \tag{2}$$

where *MI* is the Thornthwaite moisture index, *P* is precipitation (mm), and *PET* is potential evapotranspiration (mm). The *MI* is multiplied by 100 to create whole numbers (Grundstein, 2009).

The Penman-Monteith model modified by FAO was usually applied for estimating potential evapotranspiration (Thornthwaite and Mather, 1951; Jensen *et al*., 1990; Liu *et al*., 2005; Jia *et al*., 2009; Zhu *et al*., 2012).

Table 2 Climate divisions based on Thornthwaite moisture index modified by Feddema (1994)

Climate	Minimum moisture index	Maximum moisture index
Arid	–100	–66
Semiarid	–66	–33
Dry subhumid	–33	0
Wet subhumid	0	33
Humid	33	66
Perhumid	66	100

2.3.2 Kriging interpolation method

Geostatistical analysis has been the main analytical tools for studies of relationships between soil moisture and environmental factors (Nyberg, 1996; Crave and Gascuel-Odux, 1997; Bárdossy and Lehmann, 1998; Western *et al*., 1998; 1999). With the method of Kriging interpolation under ArcGIS (Goovaerts, 1997; Yamamoto, 2005; 2007), the spatial distribution of Thornthwaite moisture index was presented to research the regional difference.

The Kriging interpolation assumptions were based on spatially related prior models (Goovaerts, 1997; Yamamoto, 2005; 2007). Assumed the space of random variables possess second-order staionarity, or to obey the intrinsic spatial statistics assumptions.

3 Results and Analyses

3.1 Spatial distribution of annual Thornthwaite moisture index

The annual Thornthwaite moisture index in Hengduan Mountains was between –97.47 and 67.43, and the spatial heterogeneity was obvious in different seasons (Fig. 2). As shown in Table 3, the Thornthwaite moisture index in the north of study area was between –94.58 and 19.70 with an average value of –41.69. The value of Thornthwaite moisture index was between –97.47 and 48.67 and the average value was –37.97 in Hengduan Mountains. In the south, the value was between –84.32 and 67.43 and the average value was –11.59. The value of Thornthwaite moisture index in monsoon season was between 9.45 and 65.68 and the average value was 37.45, but in pre monsoon season was between –63.62 and –37.18 and average value was –51.63. While that in post monsoon season was between –88.44 and –42.20 with an average value of –71.99. Precipitation has great impact on the Thornthwaite moisture index. There was little precipitation in spring and winter. The annual Thornthwaite moisture index of different season was in an increasing order of winter < spring < autumn < summer. In summer and autumn with more precipitation, Thornthwaite moisture index was in an increasing order of north < middle < south. In spring with little precipitation, the evaporation was strong because the increase of temperature, and the Thornthwaite moisture index was in an increasing order of south < middle < north.

In spring, the spatial heterogeneity was obvious (Fig. 2a). The Thornthwaite moisture index in the northeast of Hengduan Mountains and the areas of three parallel rivers (Jinsha River, Lancang River and Nujiang River) were high with the average value of –20. In the east of Shaluli Mountains and from Haba Snow Mountain to Jingping Mountains, the Thornthwaite moisture index was lower and the average value was ranging from –50 to –70, other areas were between –50 and –30 in Hengduan Mountains. In summer, the Thornthwaite moisture index generally increased to 20 or more, and in different areas the moisture index did differ much (Fig. 2b). In the north, the Thornthwaite moisture index was 20–30 and that in the middle region of the Hengduan Mountains was between 30 and 40, while in the south area moisture index was the highest, which is from 40 to 50. In autumn, the Thornthwaite moisture index was dramatically declining as the monsoon retreated, which resulted in less rainfall, and the low value area began to expand, the Thornthwaite moisture index generally decreased to –10 or less (Fig. 2c). The Thornthwaite moisture index of north and middle of Jinsha River, Yalong River and Lancang River basin was the lowest, which is between –30 and –40. On the west of NuJiang River, south of Yulong Snow Mountains and east of Dadu River the Thornthwaite moisture index generally decreased to around –20. The Thornthwaite moisture index in winter was generally low (Fig. 2d), most of the areas Thornthwaite moisture index are generally lower than –40 in Hengduan Mountains (Fig. 2e). In Minya konka, Thornthwaite moisture index was between –60 and –40. Overall, the Thornthwaite moisture index of the spatial distribution was high in the south and low in the north (Fig. 2). The spatial distribution of Thornthwaite moisture index was strongly consistent with the southwest monsoon which indicated that the monsoon rainfall had a significant impact on the spatial distribution of Thornthwaite moisture index in Hengduan Mountains. Thornthwaite moisture index equivalent area was distributed along the latitude in rain seasons, and the remaining area was obviously distributed along the longitude in pre monsoon seasons and there was no obvious regularity of distribution.

3.2 Inter-decadal variation of Thornthwaite moisture index

Overall, Thornthwaite moisture index was in an obvious increasing tendency from 1960 to 2012. The Thornthwaite moisture index has increased over 1970s, 1990s respectively, whereas decreased over 1960s, 1980s and

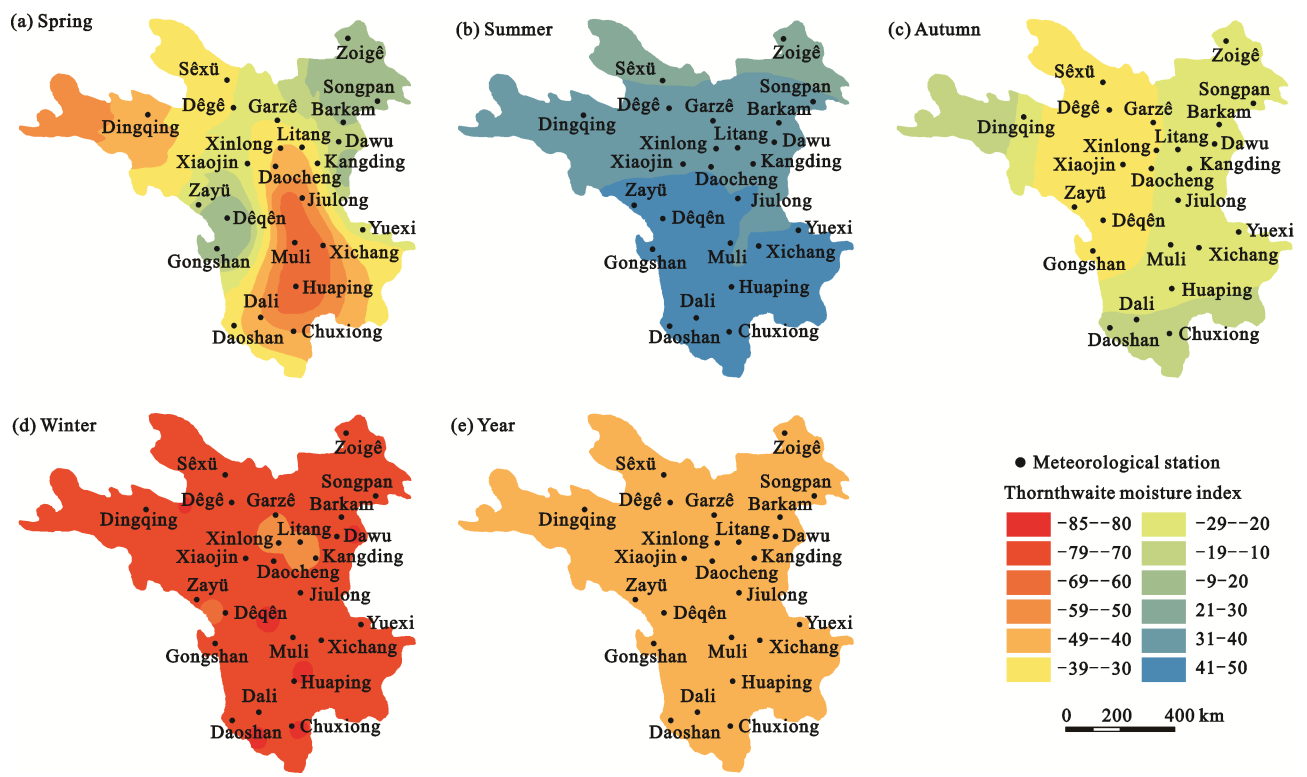

Fig. 2 Annual Thornthwaite moisture index interpolation in Hengduan Mountains during 1960–2012

Table 3 Thornthwaite moisture index of different areas in Hengduan Mountains

Area	Spring	Summer	Autumn	Winter	Pre-M	M	Post-M	Average annual
North	–37.18	19.70	–54.70	–94.58	–37.18	9.45	–85.31	–41.69
Middle	–54.09	48.67	–48.97	–97.47	–54.09	37.23	–88.45	–37.97
South	–63.62	67.43	10.74	–60.93	–63.62	65.68	–42.20	–11.59
Hengduan Mountains	–51.63	45.27	–30.98	–84.32	–51.63	37.45	–71.99	–30.42

Notes: North: the north of 31°N; middle: between 28°N to 31°N; south: the south of 28°N, which was divided according to the temperature gradient of 2.5℃. Pre-M: pre-monsoon period (from March to May); M: monsoon period (from June to October); Post-M: post-monsoon period (from November to February in next year)

2010s (Fig. 3). From 1960s to 1990s, the variation of Thornthwaite moisture index was obvious in spring (Fig. 3a). The Thornthwaite moisture index has decreased over 1960s in summer (Fig. 3b). From 1970s to 1980s Thornthwaite moisture index has remained stable for a long time. After the 1990s, it showed an increasing tendency. The abrupt variation occurred in 1993 and then the Thornthwaite moisture index increased sharply. The average Thornthwaite moisture index from 1960s to 1980s was 29.13 lower than that during 1990–2012 which was 34.16. In autumn, Thornthwaite moisture index experienced a decreasing tendency in the whole Hengduan Mountains, with the average tendency rate –0.0123/yr (Fig. 3c). In winter, there is obvious inter-decadal variation in Thornthwaite moisture index, from 1960s to 1980s Thornthwaite moisture index was volatility increased (Fig. 3d). It showed a high value range in 1990s and low value range in 2000s, the abrupt variation occurred in 1989 and 1999. The average Thornthwaite moisture index in 1990s was –63.88 which was higher than that during 1990–2012 is –72.88 (Fig. 3e).

3.3 Inter-annual variation of Thornthwaite moisture index

There is obvious spatial heterogeneity in Thornthwaite moisture index (Fig. 4), which is in the north of Hengduan Mountains. Thornthwaite moisture index increased greatly, the average inter-annual tendency rate was between 0.2–0.4. In the south of Hengduan Mountains, the Thornthwaite moisture index did not increase obviously. The average inter-annual rate was between 0 and 0.2. There is some low Thornthwaite moisture index areas distributed in the southern region of Yulong Snow Mountains, Daxue, Jingping area. In spring, the Thornthwaite moisture index of Hengduan Mountains increased obviously with the tendency rate between 0.2 and 1.0 (Fig. 4a). In the upper reaches of Dadu River, Yalong River and Jinsha River which is in the north of Hengduan Mountains, the Thornthwaite moisture index increased greatly, the average inter-annual tendency rate was between 0.6–1.0. The Thornthwaite moisture index of Minya konka and Yulong increased not obviously, the average inter-annual tendency rate was between 0.2 and 0.4, whereas in other regions was between 0.4 and 0.6. The Thornthwaite moisture index of the north Hengduan Mountains increased from west to east with the tendency rate between –0.2 and 0.2 in summer (Fig. 4b), whereas the Thornthwaite moisture index of the south Hengduan Mountains increased from south to north with the tendency rate between –0.1 and 0. In autumn, in contrast to summer, the Thornthwaite moisture index tendency rate overall was in a decreasing trend from the west to the east (Fig. 4c). Compared with other seasons, the tendency rate in winter tended to be very clear zonal differentiation, followed by decreasing Thornthwaite moisture index from north to south with the tendency rate between –0.2 and 0.6 (Fig. 4d). The high tendency rate of distribution in the upper reaches areas of Nujiang River which is in the northwest of Hengduan Mountains, formed an isolated negative tendency rate areas in Three Parallel Rivers area in the west of Hengduan Mountains (Fig. 4e).

The Thornthwaite moisture index showed a fluctuating increase tendency in Hengduan Mountains during 1960–2012 (Fig. 3) and the average annual variation tendency of Thornthwaite moisture index was 0.1938/yr (Fig. 3e). In spring, the Thornthwaite moisture index variation showed an upward trend with the variation tendency of 0.6125/yr (Fig. 3a). In summer, the Thornthwaite moisture index variation was relatively steady with a variation tendency of 0.0889/yr (Fig. 3b). In autumn, Thornthwaite moisture index decreased slightly with tendency rate of –0.0123/yr (Fig. 3c). The low relative moisture content appeared in 1981 and less precipitation was also found at the same period. In winter, the tendency rate was 0.0359/yr (Fig. 3d). The variation range of Thornthwaite moisture index in Hengduan Mountains was in descending order of spring > summer > winter > autumn. It was found that the Thornthwaite moisture index showed a consistent trend in inter annual variation and more complex in seasonal variation, indicating that the Thornthwaite moisture index variation in Hengduan Mountains would show a more distinct differentiation characteristics in a longer time, which reflect the complexity of mountain regions local topography, vegetation cover and climate change in a short time.

3.4 Meteorological factors influencing Thornthwaite moisture index

The Thornthwaite moisture index is influenced by various meteorological factors such as surface conditions and the surrounding environment (McCabe and Wolock, 1992; Willmott and Feddema, 1992; Feddema, 1994; Dai *et al*., 2004; Abdulla, 2008; Mendicino *et al*., 2008; Grundstein, 2009; Tabari and Talaee, 2013). In order to explore the reasons for the change of Thornthwaite moisture index in Hengduan Mountains, 26 meteorological factors are chosen to study the correlation between the Thornthwaite moisture index and meteorological

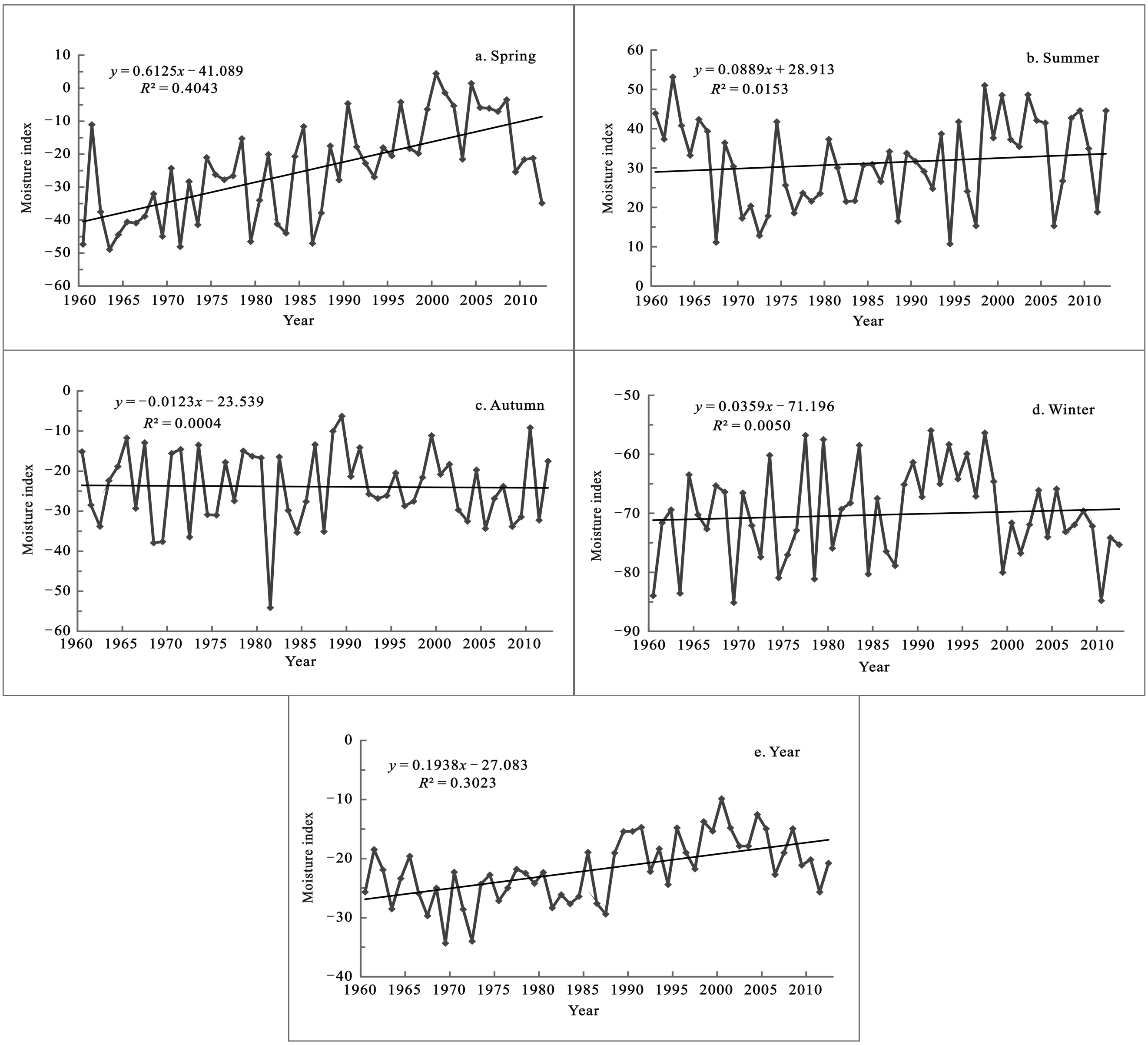

Fig. 3 Variation of Thornthwaite moisture index in Hengduan Mountains during 1960–2012

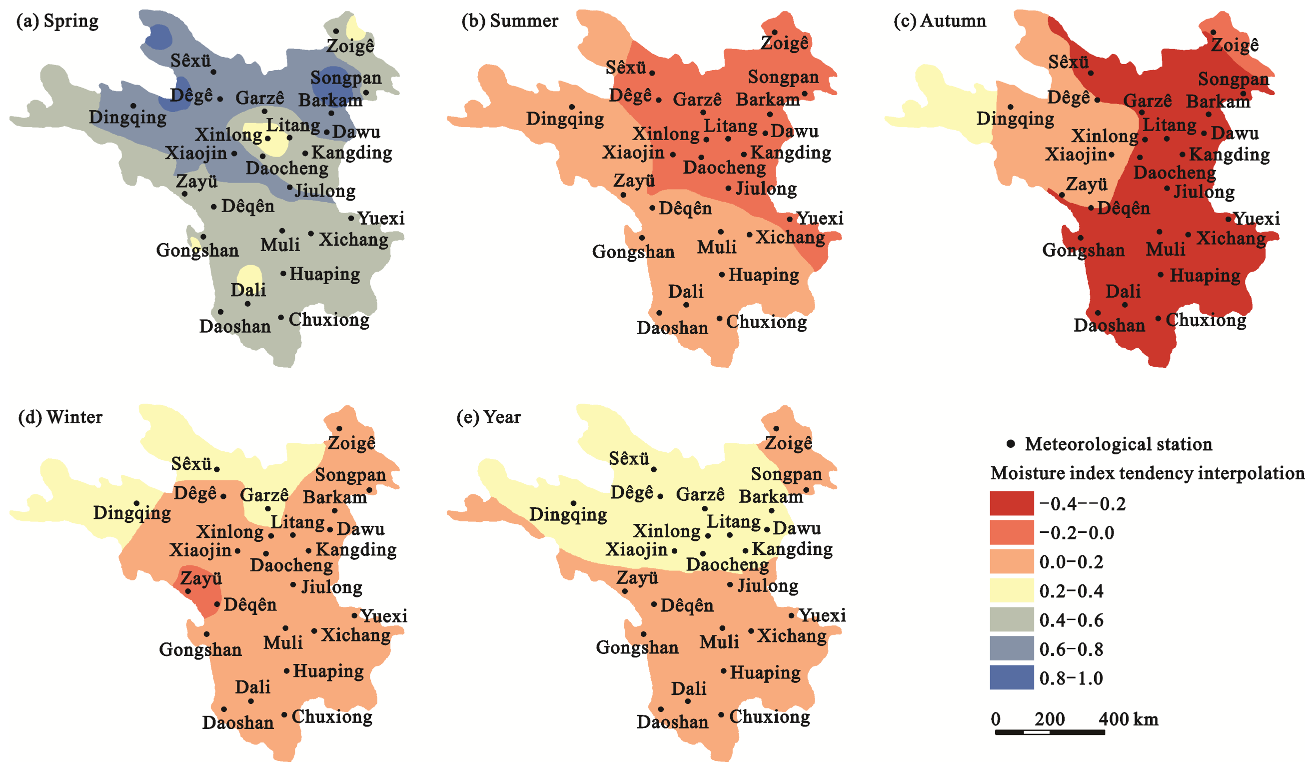

Fig. 4 Thornthwaite moisture index tendency interpolation in Hengduan Mountains from 1960–2012

factors by adopting the correlation analysis method and trend analysis approach (Table 4, Fig. 5). From Table 4, there was a great correlation among the precipitation, wind speed, sunshine duration, potential evapotranspiration and the Thornthwaite moisture index. Moreover, the controlling factors influencing the Thornthwaite moisture index varies in different seasons. As for the whole year, precipitation, wind speed, sunshine duration, and potential evapotranspiration are the main influencing factors.

3.5 Relationship between NDVI and Thornthwaite moisture index

NDVI is widely adopted to study the status quo and variation of vegetation cover in particular locations. In order to explore the relationship of Thornthwaite moisture index and NDVI in Hengduan Mountains, the correlation between the Thornthwaite moisture index and NDVI was studied by adopting the correlation analysis method (Table 5). Thornthwaite moisture index has strong correlation with vegetation cover and monthly variation (Table 5, Fig. 6). Meteorological factor had great influence on the NDVI and Thornthwaite moisture index, and varied in different seasons. In the past 18 years, NDVI and Thornthwaite moisture index showed a slightly increasing trend (Fig. 6). It can be seen that the correlation between NDVI and Thornthwaite moisture index was positive in spring and summer, but negative in autumn and winter (Fig. 6). The obvious increase of NDVI was in summer with the tendency rate of 0.0120%/yr, which shows that NDVI and Thornthwaite moisture index have the same tendency. The Thornthwaite

Table 4 Correlation analysis of Thornthwaite moisture index and meteorological elements

Moisture index	Temperature	Relative humidity	Precipitation	Wind speed	Sunshine	Potential evapotranspiration
Spring	0.269	0.345	0.599*	–0.614**	–0.342	–0.832**
Summer	–0.468	0.652**	0.810**	–0.648**	–0.755**	–0.907**
Autumn	0.071	0.462	0.028	–0.290	–0.240	–0.057
Winter	–0.379	0.202	0.113	0.369	–0.553*	–0.175
Annual	–0.169	0.450	0.658**	–0.504*	–0.573*	0.682**

Note: **: $P < 0.01$; *: $P < 0.05$

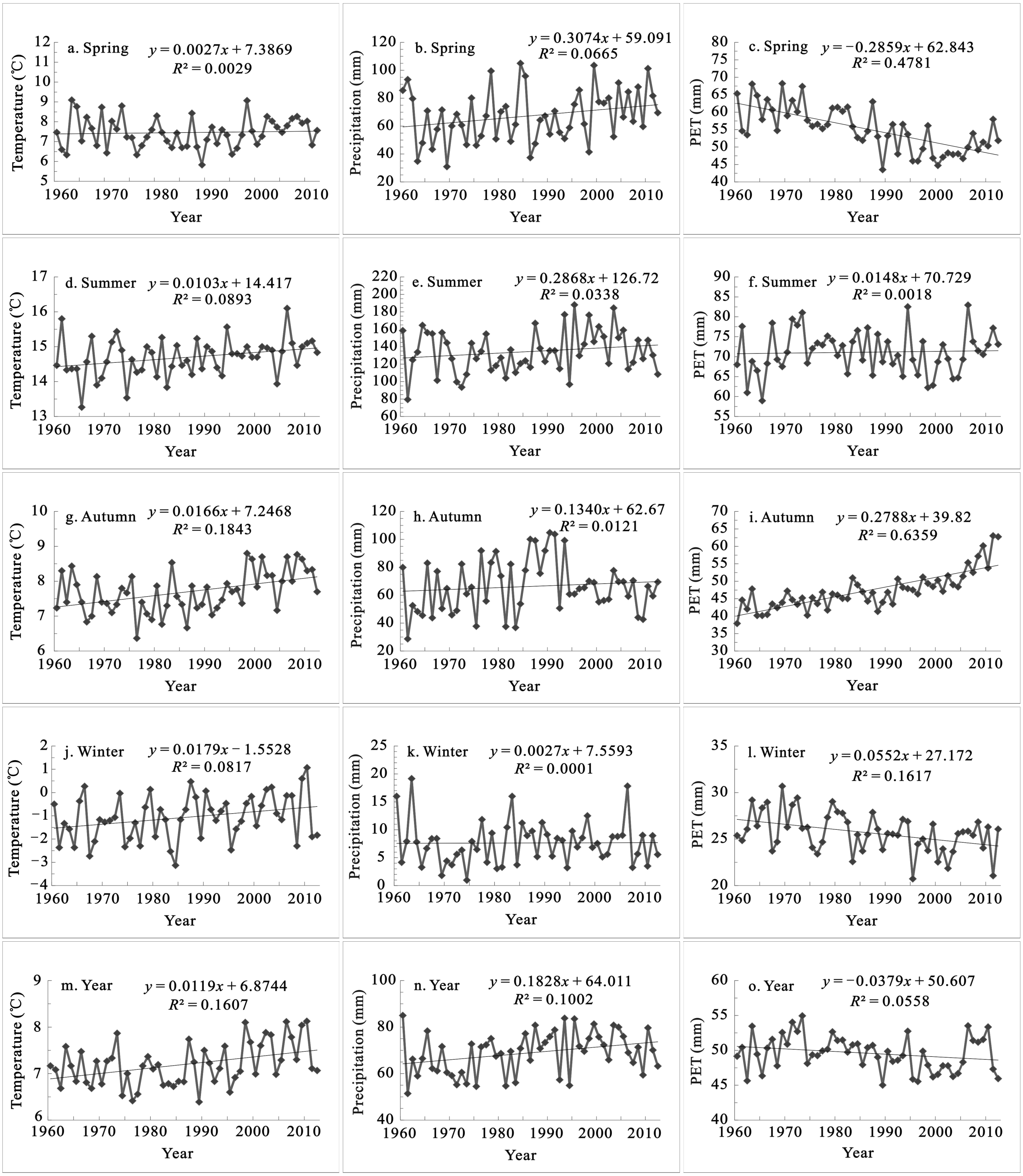

Fig. 5 Variation of meteorological elements during 1960–2012 in Hengduan Mountains. PET: potential evapotranspiration

moisture index increased as well as the NDVI rising. In spring, the increase tendency of Thornthwaite moisture index was 0.47/yr (Fig. 6a), showing that the correlation between NDVI and Thornthwaite moisture index was weak generally (r = 0.258) (Table 5). The NDVI and Thornthwaite moisture index decreased in autumn because of the decrease of precipitation and increase of potential evapotranspiration (Fig. 6c), but the Thornthwaite moisture index showed an increasing trend and NDVI decreased in winter (Fig. 6d). The smallest decrease of NDVI was in winter with the tendency of –0.0021%/yr; the correlation between NDVI and

Thornthwaite moisture index was weak generally as well. The Thornthwaite moisture index increased since February and then reached the maximum point in July and then declined, till December reached the minimum value. But the NDVI increased since April, and reached the maximum point in July and then decline till March in the following year when NDVI reach the minimum value, which showed that the Thornthwaite moisture index was more sensitive to the climate change. But NDVI had two months lag on climate change in spring.

Table 5 Correlation analysis of NDVI, soil relative moisture content and Thornthwaite moisture index

Time	NDVI	Soil relative moisture content
Spring	0.258	0.480*
Summer	0.151	0.588**
Autumn	–0.091	0.315
Winter	–0.022	–0.276
Annual	–0.040	0.252
Month	0.840**	0.269

Note: **: $P < 0.01$; *: $P < 0.05$

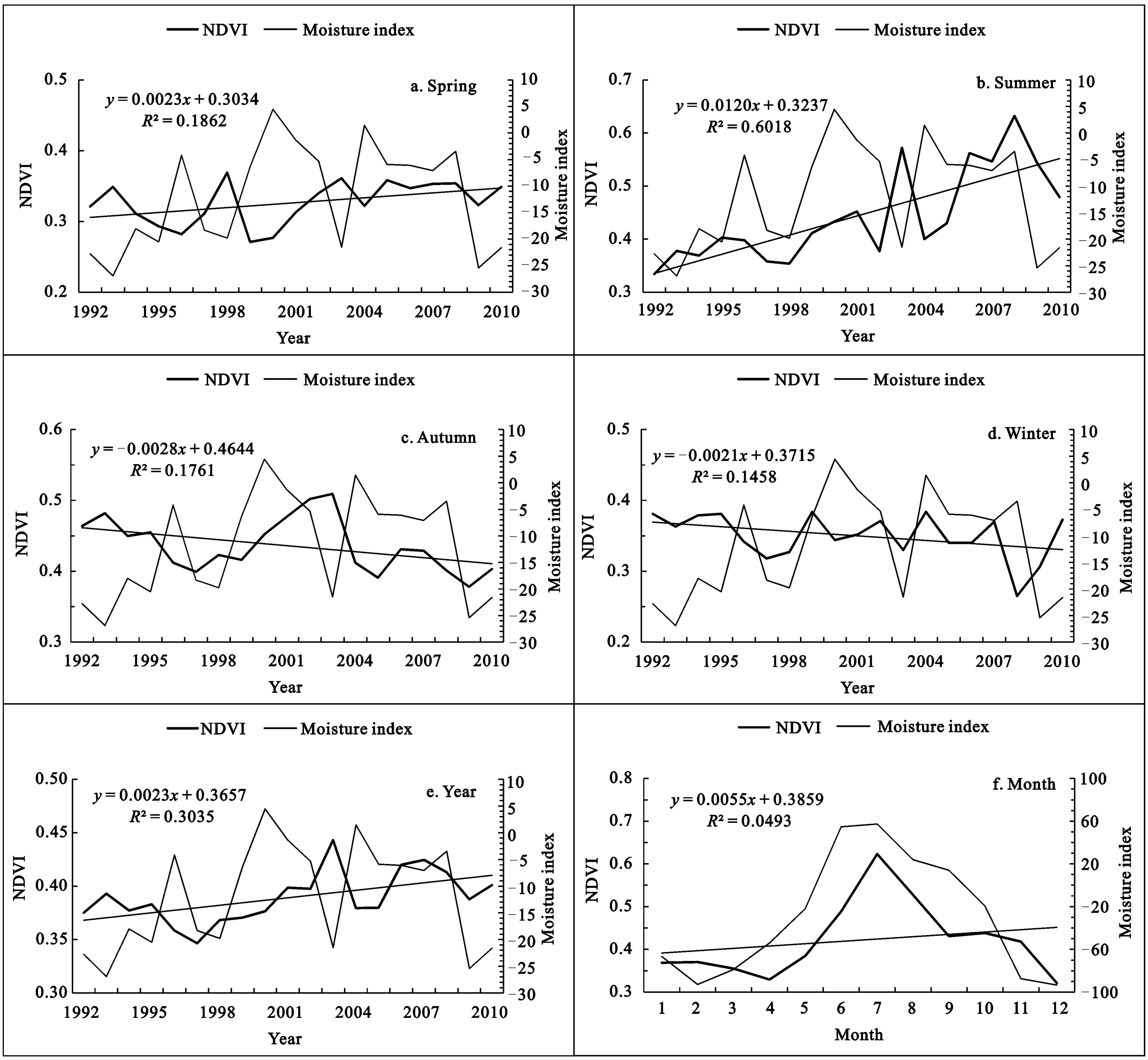

Fig. 6 Changes of NDVI (with regression model) and Thornthwaite moisture index from 1992 to 2010 in Hengduan Mountains. NDVI: Normalized Difference Vegetation Index

In the south of Hengduan Mountains, the NDVI and Thornthwaite moisture index began to rise in April, and then rise gradually and expanded to the north region. The NDVI and Thornthwaite moisture index in whole Hengduan Mountains area began to decrease significantly in September (Fig. 6f), which was almost the same with southwest monsoon variations process in Hengduan Mountains, showing the temperature, precipitation and potential evapotranspiration had a great impact on NDVI and Thornthwaite moisture index in Hengduan Mountains. Throughout the variation process, the Thornthwaite moisture index fluctuations was stronger than the NDVI, which indicated that the Thornthwaite moisture index was easier to be influenced by the external environment, the sensitivity was stronger than NDVI. The effect of climate change on the Thornthwaite moisture index was less obvious to a certain extent.

3.6 Relationship between soil relative moisture content and Thornthwaite moisture index

The dominant decreasing trend of soil relative moisture content across Hengduan Mountains in recent decades may originate from continental-scale climate variations and may be related to potential evapotranspiration decrease and precipitation increase (Zhu *et al.*, 2013). Various surface temperatures, precipitation and vegetation cover influenced soil relative moisture content (Nemani *et al.*, 1993; Sandholt *et al.*, 2002). In order to explore the relationship of soil relative moisture content and Thornthwaite moisture index in Hengduan Mountains, the correlation between the soil relative moisture content and Thornthwaite moisture index was studied by adopting the correlation analysis method (Table 5). Thornthwaite moisture index strongly correlated to soil relative moisture content in spring and summer. The influence was different in different seasons. In the past 18 years, Thornthwaite moisture index showed a slightly increasing trend (Fig. 7). It can be seen that the correlation between Thornthwaite moisture index and relative soil relative moisture content was positive in spring, summer and autumn, but negative in winter (Table 5). The increase of Thornthwaite moisture index was in spring and summer with the tendency rate of 0.61/yr and 0.09/yr, respectively (Figs. 7a and 7b), which showed that the correlation between Thornthwaite moisture index and soil relative moisture content was significant. The soil relative moisture content increased with the Thornthwaite moisture index rising. In spring, the increase tendency of soil relative moisture content was 1.0019%/yr (Fig. 7a), showing that the correlation between Thornthwaite moisture index and soil relative moisture content was strong generally (r = 0.480, P < 0.05) (Table 5). In summer, the increase tendency of soil relative moisture content was 0.7577%/yr (Fig. 7b), showing that the correlation between Thornthwaite moisture index and soil relative moisture content was also strong (r = 0.588, P < 0.01) (Table 5). Because of the decrease of precipitation and increase of potential evapotranspiration, the Thornthwaite moisture index decreased in autumn and winter, but the soil relative moisture content showed an increasing trend. The smallest increase of soil relative moisture content was in autumn and winter with the tendency rate of 0.1106%/yr and 0.3515%/yr, which showed the correlation between Thornthwaite moisture index and soil relative moisture content was weak in autumn and winter. Seeing from inter-annual variation, the Thornthwaite moisture index increased since February till July when reached the maximum point then declining till December when reaching the minimum value. But the soil relative moisture content increased since March and then declined till March in the following year when reached the minimum value, which showed that the Thornthwaite moisture index was more sensitive to the climate change, while the soil relative moisture content had 1- to 3-month lag on climate change.

3.7 Specificity of drought changes in Hengduan Mountains

Because Hengduan Mountains southern area was strongly influenced by the southwest monsoon in rainy season, precipitation, evaporation and other factors affecting Thornthwaite moisture index along the space latitudinal distribution. Then the southwest monsoon approached Hengduan Mountains inward, and the west to east blocked and north to south went through under the influence of mountains. The southwest monsoon was almost entirely extended along the longitudinal extension of mountain ranges to the north of Hengduan Mountains. Complex terrain impacted on the spatial distribution of Thornthwaite moisture index by influencing precipitation, temperature, wind speed and other climatic factors. The Thornthwaite moisture index showed

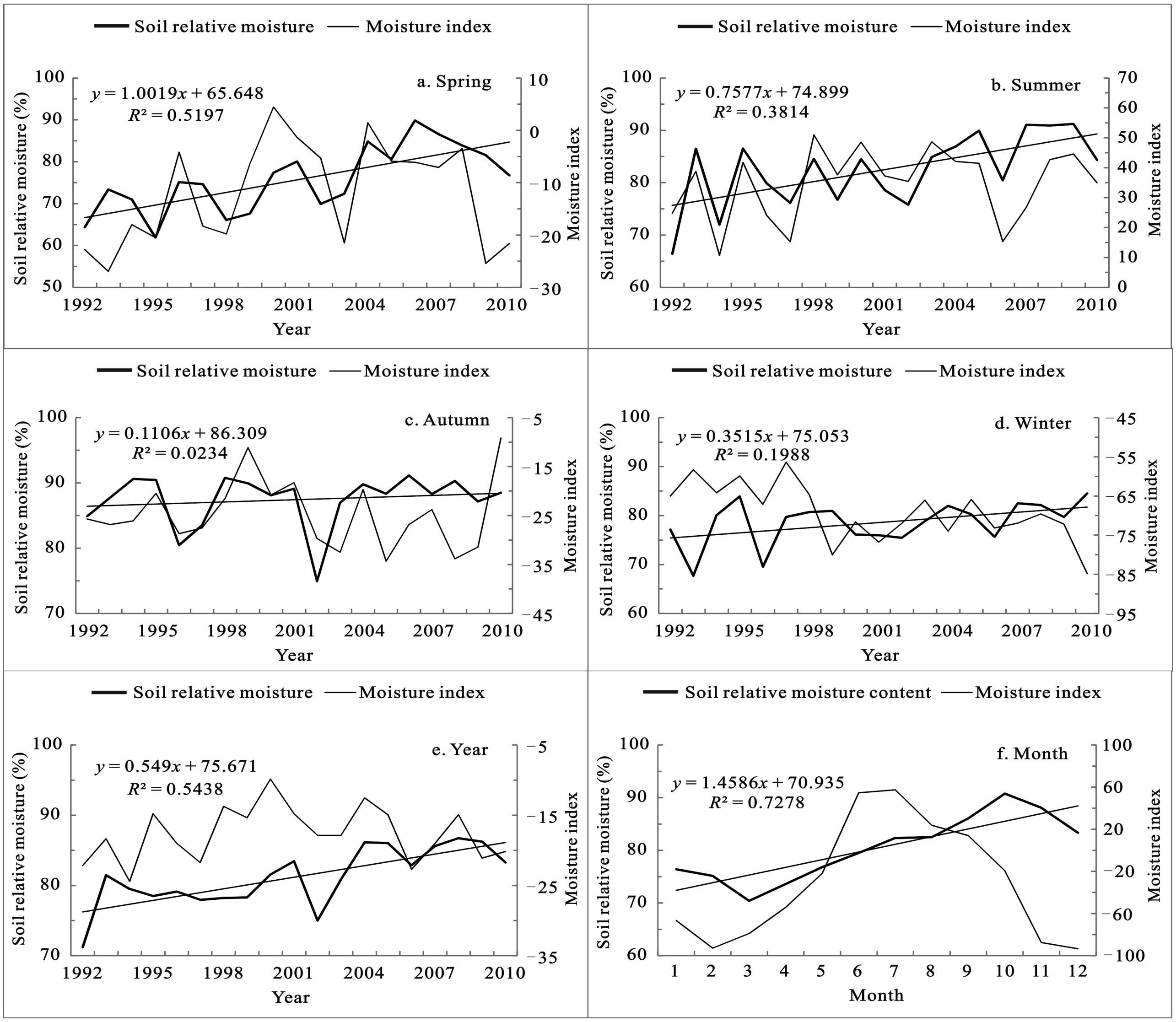

Fig. 7 Changes of soil relative moisture content (with regression model) and Thornthwaite moisture index from 1992 to 2010 in Hengduan Mountains

an increasing tendency during 1960–2012. Spatial and temporal distribution of Thornthwaite moisture index was not continuous in space from north to south. In theory, the typical mountainous terrain to a large extent will affect the distribution of temperature, precipitation, wind speed and other meteorological factors in this region, and thereby affect the spatial distribution of Thornthwaite moisture index. Overall, in summer and winter, the equivalent area of Thornthwaite moisture index extended through zonal direction, while the effect of Mountain was not obvious. In spring and autumn, the equivalent area of Thornthwaite moisture index extended to north-south direction along the longitudinal mountains. The unique ridge-gorge terrain formed the phenomenon that the continuity of water-heat distribution in the north to south was stronger than that in the east to west part, and thus determined the spatial distribution of Thornthwaite moisture index.

The amount of precipitation was relatively little in dry season, thus the Thornthwaite moisture index begins to decrease gradually since September. In early spring increasing precipitation leads to Thornthwaite moisture index rising. At the end of spring, the precipitation increase results in the rapid increase of Thornthwaite moisture index. The Thornthwaite moisture index increase since February and then reached the maximum point in July and decline till December when reaching the minimum value.

4 Conclusions

Annual Thornthwaite moisture index in Hengduan Mountains was between –97.47 and 67.43 and the spatial heterogeneity was obvious in different seasons, the Thornthwaite moisture index of the spatial distribution was high in the south and low in the north. The spatial distribution of Thornthwaite moisture index was strongly consistent with the southwest monsoon which indicated that the monsoon rainfall had a significant impact on the spatial distribution of Thornthwaite moisture index in Hengduan Mountains. Precipitation has great impact on the Thornthwaite moisture index.

Thornthwaite moisture index was in an increasing order of winter < spring < autumn < summer. It showed an obvious increasing tendency from 1960 to 2012 in the north of Hengduan Mountains, Thornthwaite moisture index increased greatly in the north and a small growth in the south of Hengduan Mountains. Variation of Thornthwaite moisture index was obvious in the Hengduan Mountains in spring. There is obvious spatial heterogeneity, which is in the north of Hengduan Mountains. Thornthwaite moisture index increased greatly, but in the south of Hengduan Mountains, it did not increase obviously.

Main meteorological factors that lead to the increase of Thornthwaite moisture index and precipitation and decrease of evaporation. Thornthwaite moisture index has strong correlation with vegetation coverage. It can be seen that the correlation between NDVI and Thornthwaite moisture index was positive in spring and summer, but negative in autumn and winter. The correlation between Thornthwaite moisture index and relative soil relative moisture content was positive in spring, summer and autumn, but negative in winter.

The typical mountainous terrain to a large extent will affect the distribution of temperature, precipitation, wind speed and other meteorological factors in this region, and thereby affect the spatial distribution of Thornthwaite moisture index. Overall, in summer and winter, the equivalent area of Thornthwaite moisture index extended through zonal direction, while the effect of Mountain was not obvious. In spring and autumn, the equivalent area of Thornthwaite moisture index extended to north-south direction along the longitudinal mountains. The unique ridge-gorge terrain formed the phenomenon that the continuity of water-heat distribution in the north to south was stronger than that in the east to west part, and thus determined the spatial distribution of Thornthwaite moisture index.

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