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Increasing free-air 0℃ isotherm height in Southwest China from 1960 to 2010

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Abstract: Based on the radiosonde data observed at 14 stations in Southwest China from 1960 to 2010, as well as the corresponding surface air temperature, the long-term change of free-air 0℃ isotherm height in Southwest China and the relationships between surface air temperature and 0℃ isotherm height are discussed. The results indicated that the spatial distribution of 0℃ isotherm height is generally related with latitude, but the huge massif or plateau may complicate the latitude pattern. The two main regimes influencing the spatial patterns of 0℃ isotherm height in Southwest China are latitude and huge massif. The annual 0℃ isotherm height has increased by 35 m per decade in the recent decades, which is statistically significant at the 0.001 level. Generally, the increasing trend can be examined for each seasonal series, especially in winter (53 m per decade). The diversity of trend magnitudes for annual and seasonal series can also be detected at a spatial view, but generally 0℃ isotherm height correlated well with surface air temperature.

Keywords: Southwest China; 0℃ isotherm height; global warming; radiosonde data

1 Introduction

In troposphere, the temperature generally decreases with the increasing of altitude, and 0℃ isotherm exist when the air temperature changes from negative to positive. The geopotential free-air 0℃ isotherm height is a critical meteorological parameter in climate change research (Diaz and Graham, 1996; Mandeep, 2009; Bradley *et al*., 2009). It can reflect the movement of cold or warm air mass, and is useful for understanding the cloud microphysical mechanism, which can provide useful information about weather forecasting and man-made weather modification (Mondal and Sarkar, 2003). In addition, compared with the surface air temperature measured near ground, the 0℃ isotherm height are less influenced by the human process, such as urbanization and heat island effect. Due to the physical significance of 0℃ isotherm, the freezing and thawing process in high altitude is related with 0℃ isotherm

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height (Zhang and Guo, 2011; Zhang *et al*., 2009, 2012). In the past decades, many researches focused on the 0℃ isotherm height in different regions of China (especially the arid Northwest China) and its significance in reconstructing historic runoff, reflecting cryospheric change, forecasting high-altitude discharge and so on (Chen *et al*., 2012; Mao *et al*., 2004; Zhang *et al*., 2005, 2010, 2009; Li *et al*., 2006; Wang *et al*., 2008b; Huang *et al*., 2013; Pan *et al*., 2012).

Southwest China, mainly containing the Tibetan Plateau (including the surrounding mountain ranges such as the Hengduan Mountains), the Yunnan-Guizhou Plateau and the Sichuan Basin, shows complex climate types, and this region have experienced significant climate change in the past decades (Li *et al*., 2012a, 2012b). The frequent drought during spring and summer in Southwest China have also arouse great attention (Zhang *et al*., 2013), which is related to food supplies and downstream water crisis. Besides the ground meteorological observation, the climate change also can be found for the free-air temperature and geopotential height. Compared with the above-mentioned researches in Northwest China, few attentions have been paid to the long-term 0℃ isotherm height in Southwest China. In this paper, based on the radiosonde series in the past half century, the variation of 0℃ isotherm height are analyzed on an annual and seasonal basis, and the relationship with surface air temperature is yielded.

2 Data and methods

2.1 Data

In this study, Southwest China includes five administrative subregions (province, autonomous region or municipality), namely, Sichuan Province, Yunnan Province, Guizhou Province, Guangxi Zhuang Autonomous Region and Chongqing Municipality. The monthly radiosonde data (temperature and geopotential height for mandatory pressure level) and surface meteorological data (monthly mean temperature) are provided by the National Meteorological Information Center (NMIC) of China Meteorological Administration (CMA). To ensure the data continuity and integrity, 14 meteorological stations during 1960–2010 in the study region are selected (Figure 1). All the radiosonde data are measured twice a day, i.e. 0:00 UTC (Universal Time Coordinated) (8:00 Beijing Time) and 12:00 UTC (20:00 Beijing Time).

The inhomogeneity of radiosonde data in China has been widely reported (Zhang and Guo, 2011), which is mainly caused by equipment update, calculation method change, station relocation, etc. In order to remove the effect of inhomogeneity in trend assessment, the penalized maximal F test (Wang *et al*., 2008a) was applied in this study. The detected change points were adjusted with the supporting of metadata. This method of homogeneity test and adjustment is widely used in previous research (Xu *et al*., 2013; Huang *et al*., 2013).

2.2 Method

2.2.1 0℃ isotherm height calculation

If known as geopotential height and air temperature for specific pressure level, free-air 0℃ isotherm height can be calculated by using linear interpolation (Bradley *et al*., 2009). The

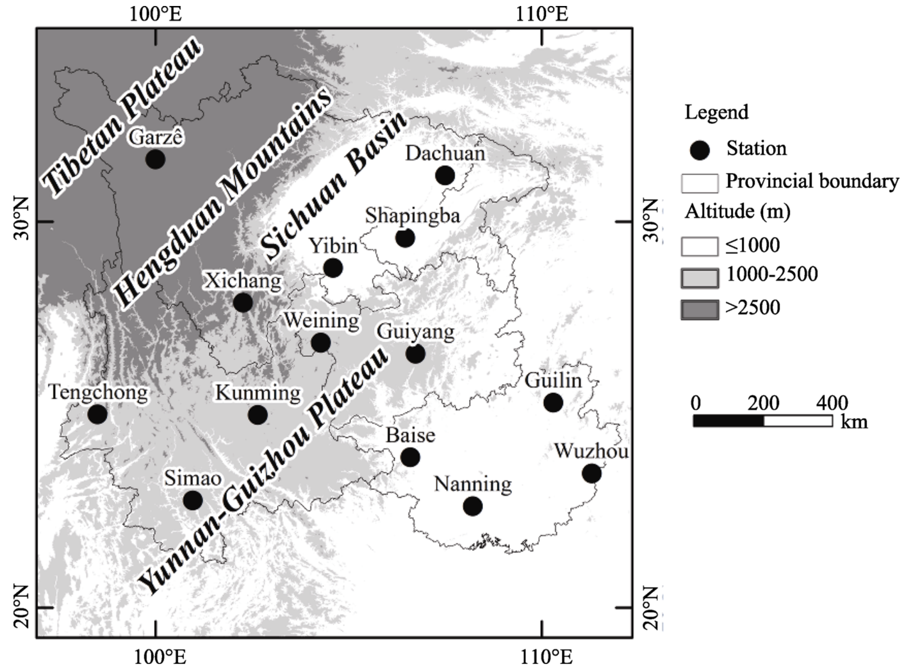

Figure 1 Location of radiosonde stations in Southwest China

two pressure levels with air temperature nearest to 0℃ should be selected, and then the 0℃ isotherm height can be interpolated by using the following formula:

$$H = T_{\text{down}} \frac{H_{\text{down}} - H_{\text{up}}}{T_{\text{up}} - T_{\text{down}}} + H_{\text{down}} \tag{1}$$

where H represents the 0℃ isotherm height in geopotential meters, H_{up} and H_{down} (and T_{up} and T_{down}) represent the geopotential heights (and air temperature) of the nearest two standard pressure level to 0℃ isotherm, respectively. Three standard pressure levels (500 hPa, 700 hPa and 850 hPa) are used for the study area.

In this study, 0℃ isotherm height for the two time series (0:00 and 20:00 UTC) are calculated, respectively, and then the two height series are averaged to acquire the monthly series. Seasonal mean value of 0℃ isotherm height are calculated by using corresponding three months, i.e. spring (MAM), summer (JJA), and autumn (SON) and winter (DJF).

2.2.2 Sen's slope estimation

The non-parametric Sen's method (Sen, 1968) is used to estimate the linear trend of regression, and Sen's slope is not significantly affected by single data errors or outliers. Firstly, the slopes (S_i) of all data value pairs are calculated as

$$S_i = \frac{x_j - x_k}{j - k} \tag{2}$$

where $j>k$.

If there are n values x_j in the time series, we can get S_i as many as $N=n(n-1)/2$. The Sen's slope is the median of these N values of S_i.

If N is odd,

$$S_{\text{median}} = S_{(N+1)/2} \tag{3}$$

If N is even,

$$S_{\text{median}} = \frac{S_{N/2} + S_{(N+2)/2}}{2} \tag{4}$$

2.2.3 Mann-Kendall test

The non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) is used to examine the statistical significance in this study. The Mann-Kendall test statistic Z is given as

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\text{var}(S)}}, & S>0 \\ 0, & S=0 \\ \dfrac{S+1}{\sqrt{\text{var}(S)}}, & S<0 \end{cases} \tag{5}$$

The statistic S is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \tag{6}$$

where x_j and x_i are the annual values in years j and k (j>k), respectively, and

$$\text{sgn}(x_j - x_i) = \begin{cases} 1, & x_j - x_i > 0 \\ 0, & x_j - x_i = 0 \\ -1, & x_j - x_i < 0 \end{cases} \tag{7}$$

If n is no less than 10, the normal approximation test is used. When several tied values (i.e. equal values) exist in time series, it may reduce the validity of normal approximation if the number of values is close to 10. So the variance of S is calculated as

$$\text{var}(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)}{18} \tag{8}$$

where q is the number of tied groups and t_p is the number of data values in the pth group.

Positive Z value indicates an increasing trend, while negative value indicates a decreasing trend. To test the significance at α level (α=0.05, 0.01 or 0.001), a null hypothesis of no trend H_0 is rejected if the absolute value of Z is larger than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ can be obtained from standard normal cumulative distribution tables.

2.2.4 Other method

ArcGIS 9.3 was used to map the spatial distribution of mean and trend magnitudes for each station.

3 Results and analysis

3.1 Spatial distribution of 0℃ isotherm height

Figure 2 shows the spatial distribution of seasonal and annual 0℃ isotherm height. It is clear that 0℃ isotherm height in warm summer is higher than that in cold winter. The mean value

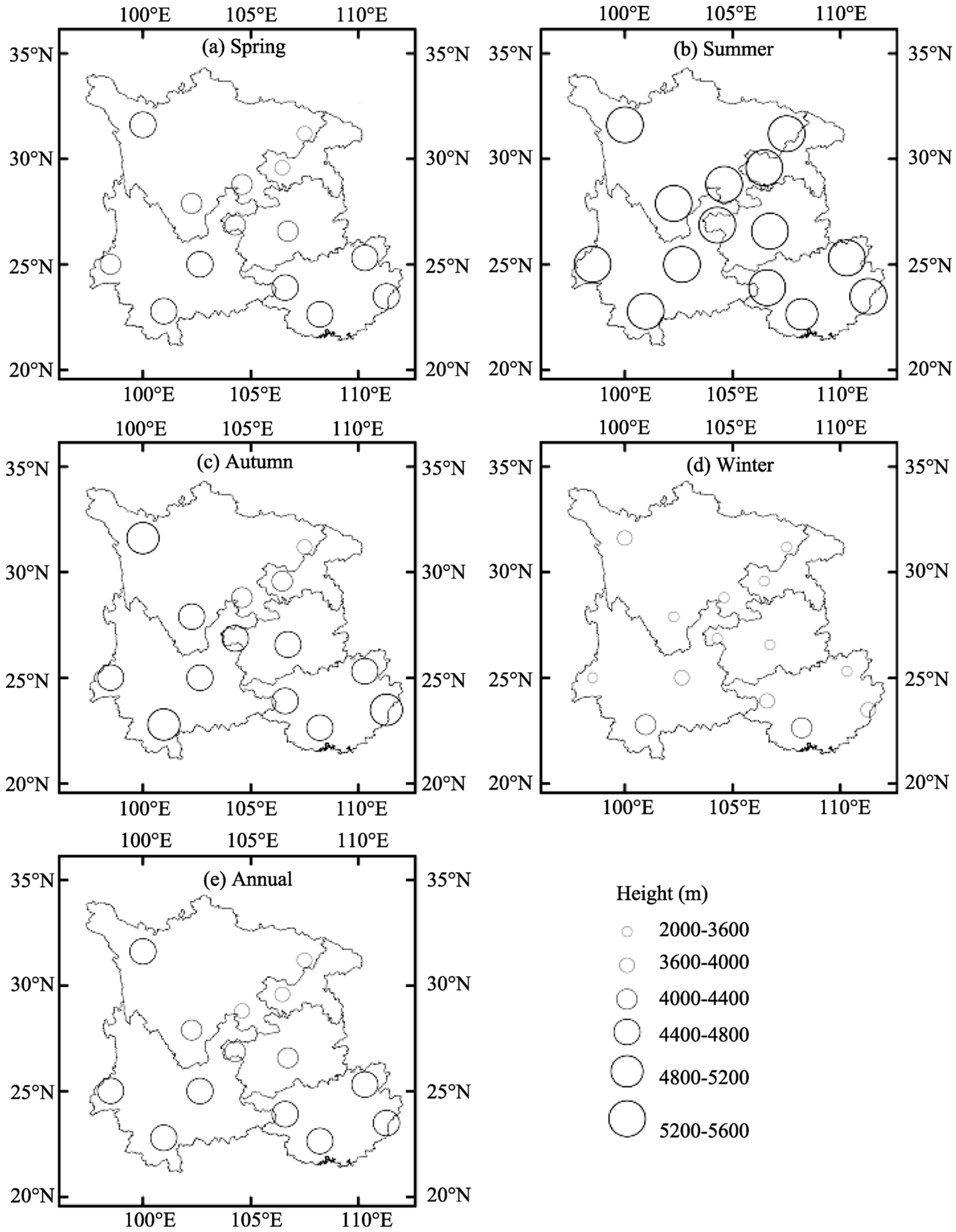

Figure 2 Spatial distribution of seasonal/annual 0℃ isotherm height in Southwest China during 1960–2010

of 0℃ isotherm height in the 51 years for each station in summer ranges from 5109 m to 5594 m, and that in winter changes between 2002 m and 4354 m. Generally, the spatial distribution of 0℃ isotherm height is latitude dependent, which means that the northern stations usually have lower 0℃ isotherm heights, and the southern stations show slightly higher 0℃ isotherm heights. 0℃ isotherm height in summer is generally well-distributed with small difference. On an annual basis, the maximum value 4785 m can be found in Simao, and the minimum value 3736 m exists in Dachuan. The spatial distribution of annual series is similar to that in spring, autumn and winter, which present gradually increasing trend from north to south. Compared with the Sichuan Basin (including Yibin, Shapingba and Dachuan) with similar latitudes, 0℃ isotherm height at Garzê in the Hengduan Mountains shows higher value.

The box plots of seasonal and annual 0℃ isotherm height for each station in Southwest China are shown in Figure 3. The lower (upper) boundary of the box indicates the 25th (75th) percentile. The whiskers above and below the box indicate the 90th and 10th percentiles, and the points above and below the whiskers indicate 95th and 5th percentiles. In Figure 3, we arrange the stations with an increasing latitude order. It is clear that the spatial distribution of 0℃ isotherm height is related with latitude, and 0℃ isotherm height in Southwest China generally shows a reducing trend from south to north except in summer. However, in Garzê, a station located in the Hengduan Mountains (eastern margin of the Tibetan Plateau), 0℃ isotherm height is significantly higher than the stations with similar latitude. 0℃ isotherm height in winter for each station shows the largest diversity among the four seasons, while the difference in summer for each station is not so significant.

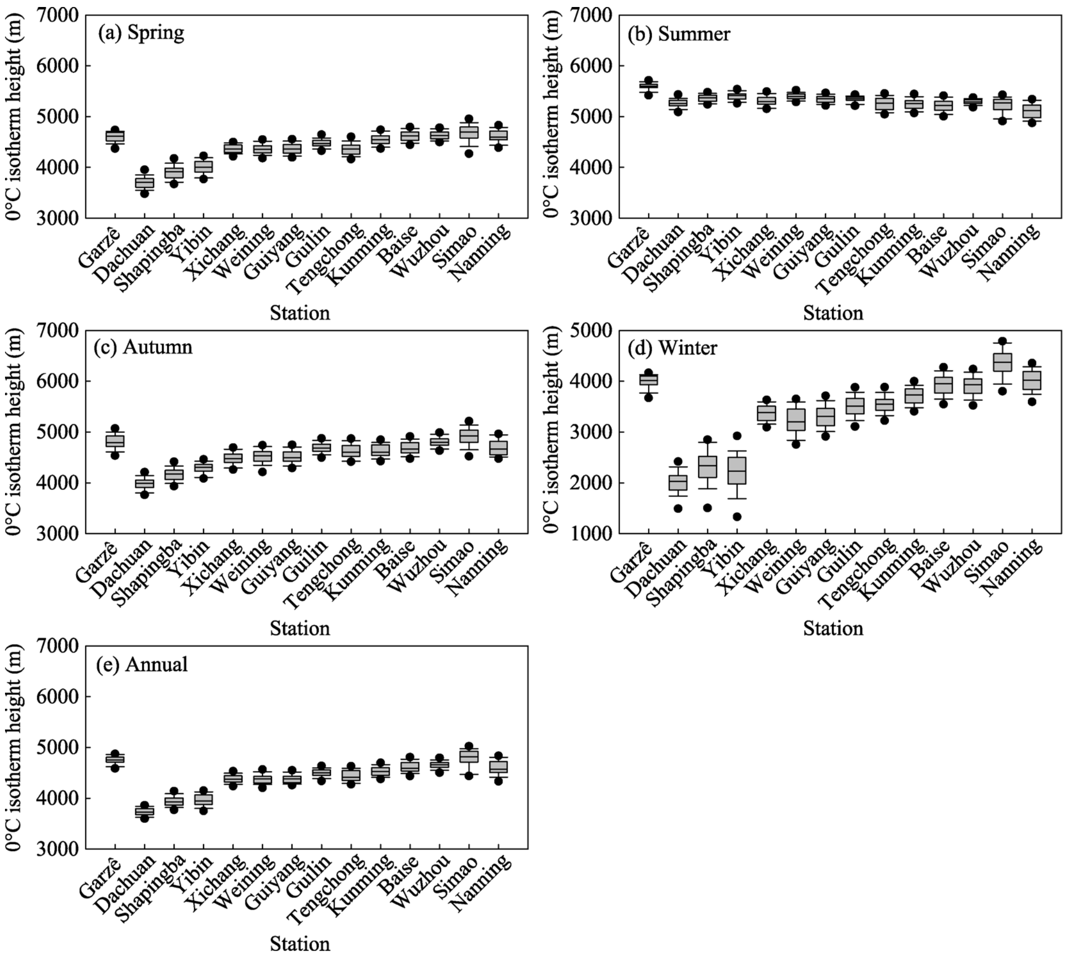

Figure 3 Box plot of seasonal/annual 0℃ isotherm height in Southwest China during 1960–2010

Previous studies (Zhang and Guo, 2011) show that 0℃ isotherm height in China generally exhibits latitudinal zone, and inclined from north to south, which is coincident with the main spatial pattern in Southwest China calculated in this study. It also indicates that 0℃ isotherm height is a meteorological parameter reflecting free-air physical attribute, and can not be influenced by the surface human effect and small-scale topography. However, huge massif or plateau may complicate the latitude pattern. The abnormal high value of 0℃ isotherm height in Garzê is an example of effect of the Tibetan Plateau. With the influence of the high altitude, the surface air temperature in Garzê is generally lower than the similar latitudes such as Dachuan and others. Therefore, the two main regimes influencing the spatial patterns in Southwest China are latitude and huge massif.

3.2 Annual variation of 0℃ isotherm height

Table 1 shows the decadal anomalies of 0℃ isotherm height in the study area during 1960–2010. On an annual basis, for the 1960s, 1970s and 1980s, 0℃ isotherm height in Southwest China shows negative anomaly, and positive anomaly can be found in the latest two decades. The decadal mean is –64 m, –43 m, –1 m, 42 m and 60 m for the 1960s, 1970s, 1980s, 1990s and 2000s, respectively, in which the lowest is shown for the 1960s. The annual series at 0:00 UTC and 12:00 UTC shows similar pattern, which means that the increasing trend exists in different time series. More details about seasonal series are also shown in Table 1.

Table 1 Decadal anomalies of 0℃ isotherm height in Southwest China during 1960–2010

Decade	0℃ isotherm height anomalies (m)														
	Spring			Summer			Autumn			Winter			Annual		
	0:00	12:00	Ave.	0:00	12:00	Ave.	0:00	12:00	Ave.	0:00	12:00	Ave.	0:00	12:00	Ave.
1960–1969	–30	–31	–31	–48	–93	–70	–55	–70	–62	–108	–85	–94	–56	–66	–64
1970–1979	–13	–10	–11	–53	–51	–52	–70	–67	–68	–64	–40	–53	–48	–40	–43
1980–1989	–35	–30	–31	25	20	22	16	12	14	–3	4	1	–3	–2	–1
1990–1999	41	37	39	50	54	52	46	44	45	34	1	7	47	36	42
2000–2010	34	31	33	24	64	44	57	74	65	124	110	117	54	65	60

In Figure 4, 0℃ isotherm heights in Southwest China have increased for different seasonal series. The trend magnitudes of 0℃ isotherm heights in spring, summer, autumn and winter are 21 m, 35 m, 37 m and 53 m per decade, respectively. Winter is a season with the highest trend magnitude and spring has the lowest magnitude. The linear trend is statistically significant at the 0.01 level in spring and winter as well as at the 0.001 level in summer and autumn. In addition, the fluctuation of 0℃ isotherm height in winter is the largest among the four seasons. On an annual basis, 0℃ isotherm height has increased by 35 m per decade during 1960–2010, which is statistically significant at the 0.001 level. The increasing 0℃ isotherm height indicates that the free-air has experienced a significant warming trend, which is coincident with the global warming.

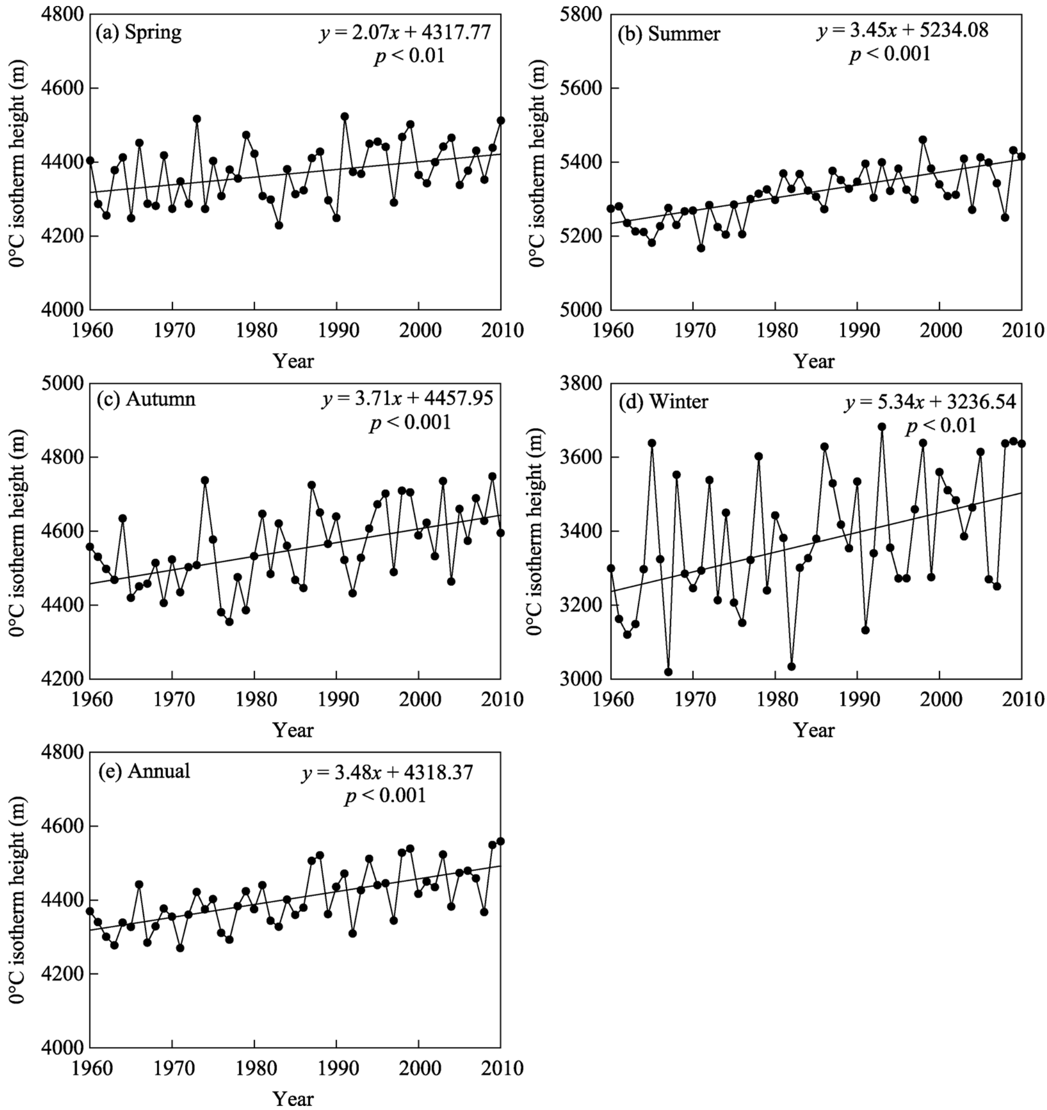

Figure 4 Variation of seasonal/annual 0℃ isotherm height in Southwest China during 1960–2010

The trend magnitudes at 0:00 UTC and 12:00 UTC are slightly different, although the increasing trend can be generally detected in the study area (Table 2). In summer and autumn, the trend magnitude is larger in 12:00 UTC than that in 0:00 UTC. However, in spring and winter, the trend in 12:00 UTC is relatively lower. Winter usually shows the highest trend

Table 2 Trend magnitude of seasonal/annual 0℃ isotherm height in Southwest China during 1960–2010

	Spring		Summer		Autumn		Winter		Annual	
	Trend (m/a)	Sig.	Trend (m/a)	Sig.	Trend (m/a)	Sig.	Trend (m/a)	Sig.	Trend (m/a)	Sig.
0:00	2.1	<0.01	2.7	<0.001	3.3	<0.01	6.3	<0.01	3.3	<0.01
12:00	2.0	<0.01	4.2	<0.001	4.0	<0.001	4.7	<0.01	3.5	<0.001
Ave.	2.1	<0.01	3.5	<0.01	3.7	<0.001	5.3	<0.01	3.5	<0.001

among the four seasons, with a rate of 63 m per decade in 0:00 and 47 m per decade in 12:00, respectively. On an annual basis, 0℃ isotherm height has increased by 33 m per decade and 35 m per decade in 0:00 UTC and 12:00 UTC, respectively.

3.3 Spatial distribution of trend in 0℃ isotherm height

The spatial pattern of trend magnitude of 0℃ isotherm height is much complex (Figure 5).

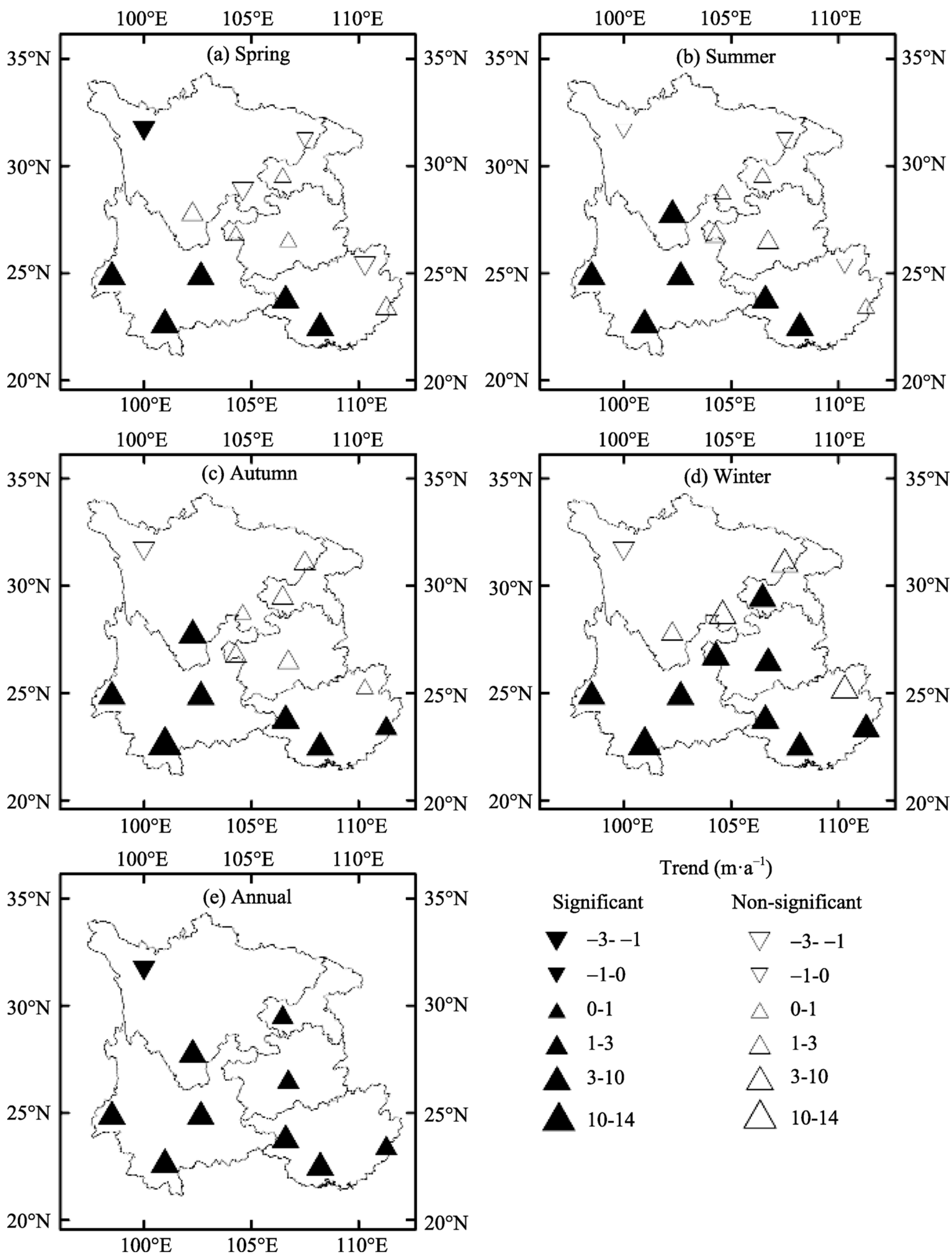

Figure 5 Spatial distribution of trend magnitude in 0℃ isotherm height in Southwest China during 1960–2010

Similar as the long-term trend mentioned above, 0℃ isotherm heights at most stations in Southwest China generally show rising trend. Trend magnitude of 0℃ isotherm height in different seasons over Southwest China shows significant spatial diversity. Yibin, Dachuan and Guilin show slightly deceasing trend in spring and/or summer. Garzê, a station located in the Hengduan Mountains shows decreasing trend in each season, especially in spring (–22 m per decade). The proportion of stations with increasing trend is 78.57%, 85.71%, 92.86% and 92.86% for spring, summer, autumn and winter, respectively. 35.71%, 42.86%, 50.00% and 64.29% of the stations have linear trend significant at the 0.05 level. In addition, the trend magnitude in winter is much larger than other seasons. Detailed trend magnitudes for each station at 0:00 UTC and 12:00 UTC are shown in Table 3, respectively.

Table 3 Trend magnitude in seasonal/annual 0℃ isotherm height for each station in Southwest China during 1960–2010

	Trend magnitude (m/a)														
	Spring			Summer			Autumn			Winter			Annual		
	0:00	12:00	Ave	0:00	12:00	Ave	0:00	12:00	Ave	0:00	12:00	Ave	0:00	12:00	Ave
Garzê	–1.4	–2.9**	–2.2*	–0.6	–0.8	–0.5	–1.5	–2.5	–2.3	–1.9	–2.1	–1.6	–1.8	–2.2**	–1.8*
Dachuan	0.5	–1.5	–0.4	–0.3	0.0	–0.2	1.5	0.9	1.1	–1.8	8.4**	3.6	–0.6	1.4	0.2
Shapingba	–0.2	0.7	0.2	0.3	1.4	0.9	1.51	2.7*	2.1	10.4**	8.2**	9.5**	2.0	2.6*	2.0*
Yibin	–3.8*	–0.4	–2.2	–5.0***	5.7***	0.5	–1.0	2.2*	0.6	14.6***	–3.0	6.2	0.4	0.4	0.3
Xichang	0.7	2.0**	1.4	2.5**	8.40***	5.6***	1.6	4.0***	3.0*	2.5	2.2	2.4	1.7	4.3***	3.2***
Weining	–0.1	0.3	0.3	0.6	1.2	1.0	1.6	1.7	1.6	7.1*	6.0*	6.4*	1.8	2.2*	2.0
Guiyang	–0.5	0.9	0.2	–0.5	2.8***	1.1	1.0	2.6*	1.8	5.3*	4.7*	5.4*	0.9	2.9**	1.9*
Guilin	–0.6	–2.5**	–1.7	0.3	–2.3***	–1.0	1.3	0.5	0.7	4.6*	2.8	3.8	1.0	–0.7	0.7
Tengchong	3.4**	7.3***	5.4***	2.0**	13.0***	7.5***	3.5**	11.2***	7.3***	6.4***	5.0***	5.8***	3.9***	9.1***	6.6***
Kunming	9.9***	–0.9	4.7***	12.3***	0.2	6.3***	9.1***	0.6	4.8***	6.4***	1.9	4.0*	9.6***	0.2	5.0***
Baise	2.8***	6.7***	4.8***	4.4***	9.7***	7.1***	4.3***	8.9***	6.6***	4.5*	7.6***	6.0**	3.9***	8.3***	6.0***
Wuzhou	1.19	1.3	1.4	–0.2	1.6*	0.7	2.5*	3.3***	2.8**	4.9*	4.7*	4.7*	1.7*	2.6***	2.1**
Simao	12.9***	6.0***	9.3***	13.9***	3.2***	8.6***	15.2***	5.5***	10.4***	16.0***	9.5***	12.8***	14.1***	5.8***	9.7***
Nanning	3.72***	10.48***	7.11***	5.34***	13.66***	9.46***	4.75***	12.56***	8.89***	6.32**	12.27***	9.32***	4.71***	12.06***	8.84***

Note: *, **, and *** denote statistically significant at the 0.05, 0.01, and 0.001 levels, respectively.

On an annual basis, 0℃ isotherm height over Southwest China shows entirely rising trend except in Garzê (–18 m per decade), and 92.86% of the stations have annual increasing trend, of which 64.28% is statistical significant at the 0.05 level. Simao in Yunnan Province shows the most significant increasing trend (97 m per decade). The variation trend of 0℃ isotherm height in Southwest China is significant with change of altitude, of which the trend magnitude gradually increases from north to south as well as the number of significant stations. Stations at the southern part of Southwest China usually have increasing trend with statistical significance at the 0.05 level.

Global warming has been widely reported in China, including Southwest China (Li *et al*., 2012b). Figure 6 shows the comparison between trend magnitudes of surface air temperature and 0℃ isotherm height for different meteorological stations in Southwest China during

1960– 2010. Most stations have the same trend of increasing or decreasing, except Dachuan in the northern part of the study area. Generally, warming trend derived from surface air temperature observation can be examined for most stations. The trend of 0℃ isotherm height is generally related with surface air temperature, which is similar with the previous researches (Huang *et al.*, 2011; Ma *et al.*, 2011).

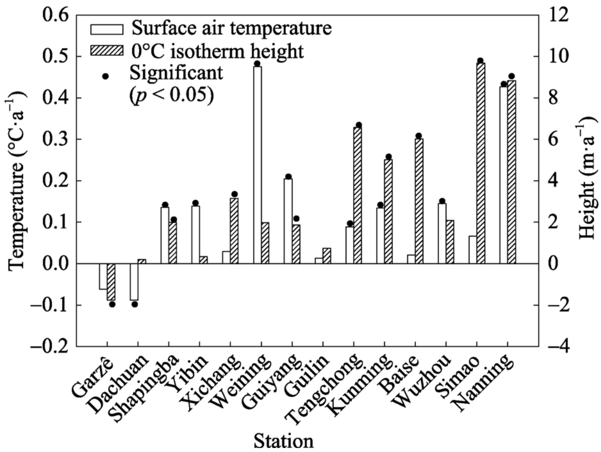

Figure 6 Trend magnitudes of surface air temperature and 0℃ isotherm height in Southwest China during 1960–2010

4 Conclusions

The long-term changes of 0℃ isotherm height in Southwest China during 1960–2010 are analyzed in this study. The spatial distribution of 0℃ isotherm height is generally related with latitude, and 0℃ isotherm height in Southwest China generally shows an increasing trend from north to south except in summer. However, huge massif or plateau may complicate the latitude pattern. Therefore, the two main regimes influencing the spatial patterns of 0℃ isotherm height are latitude and huge massif.

Generally, 0℃ isotherm height in this region shows an increasing trend, especially in winter with an increasing rate of 53 m per decade. The increasing 0℃ isotherm height indicates that the free-air has experienced a significant warming trend, which is coincident with the global warming. 0℃ isotherm height at most stations in Southwest China shows rising trends, and the trend of 0℃ isotherm height is generally related with surface air temperature.

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