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Short Communication

Observed air/soil temperature trends in open land and understory of a subtropical mountain forest, SW China

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ABSTRACT: This study seeks a further understanding on climate trends in a subtropical mountain forest, SW China. Air (T_a) and soil temperature (T_s), both in open land (1983–2010) and under a forest canopy (1986–2010), were investigated. Short-term radiation components were also measured simultaneously both in open land and understory to explore the relationships of microclimatic variables. Correlations of T_a and T_s with sunshine hours (S_t) and wind speed (W_s) were also analysed as driving factors of the temperature trends.

The results showed that (1) Understory radiation components were greatly reduced by the forest canopy, showing a strong effect of forest canopy on microclimatic variables. T_s_0 in open land was significantly correlated with solar radiation. Wind speed had significant influences on differences between T_a and T_s_0, between open land T_s_0 and understory T_s_0. The long-term data showed that T_s_0 under forest canopy were closely coupled with T_a in open land. (2) T_a had a larger increase than T_s_0 in open land, and temperature increases in winter were greater than in other seasons. Soil temperature at depths under forest canopy had nearly twice the increases of those on open land; we attributed this to the higher relative increase of W_s over S_t. (3) A slope change in 1998 was detected in the T_s_0 and T_a difference ($T_s\_0 - T_a$) series, suggesting different response of T_s_0 and T_a since that year. Deceleration of S_t and stability of W_s may have been factors.

This study improves our understanding of warming in a nature reserve where anthropogenic influences are absent. Further studies are needed for the biological and biochemical implications on subtropical mountain forest. Copyright © 2012 Royal Meteorological Society

KEY WORDS trend analysis; microclimate; radiation budget; under forest canopy; sunshine hours; wind speed; Ailaoshan National Nature Reserve

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1. Introduction

Over the past century, global average air temperatures have increased by 0.07 °C per decade (1901 ∼ 2005), with radiative-transfer models projecting a further 1.8–4.0 °C increase by 2100 (IPCC, 2007). In China, air temperature has increased by 0.27 °C per decade from 1961 to 2003 with accelerating trends after 1990 (Liu *et al*., 2004). However, few studies have examined corresponding trends in soil temperature (Jacobs *et al*., 2011).

Soil temperature controls the biological and ecological processes through the limitations on plant growth and forest distribution (Körner and Paulsen, 2004). Soil respiration, which has a substantial effect on atmospheric carbon cycling, is sensitive to changes in soil temperature (Bond-Lamberty and Thomson, 2010). As soil temperature may differ from air temperature, exploring trends in both soil and air temperature could improve our understanding of warming and its biological and biochemical consequences.

Few long-term soil temperature, trends have been reported, with most from open land meteorological stations (García-Suárez and Butler, 2006; Subedi and Fullen, 2009). However, those trends may not well represent those from under forest canopies. Previous studies

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comparing forest and open land temperatures were based on short data series and focused on temperature extremes (Morecroft *et al.*, 1998; Paul *et al.*, 2004; Renaud and Rebetez, 2009). Long-term temperature trends under forest canopies have been examined in one study of temperature extremes under forest cover with different elevations, aspects and forest types (Ferrez *et al.*, 2011). Consequently, comparing temperature trends under forest canopies with those more commonly measured in open lands should improve our understanding of warming in forested areas.

This study took place in a mountain forest area south-west China and addresses the following questions: (1) What are the microclimatic differences between open land and under forest canopy? (2) What is the pattern of air/soil temperature trends both in open land and under forest canopy? (3) When does soil temperature respond differently than air temperature in open land?

2. Study site and methods

2.1. Study site

The Ailaoshan Station for Subtropical Forest Ecosystem Studies (ASSFE, 24°32′N, 101°01′E and 2480 m asl.) is located in Jingdong County, Yunnan Province and the northern part of Ailaoshan Natural Reserve (Figure 1). Subtropical montane evergreen broad-leaved forest (dominated by *Castanopsis wattii* and *Lithocarpus xylocarpus*) persists in Ailaoshan Natural Reserve. The strata of this forest include canopy (18–25 m), shrub (1–3 m) and herb layers (<0.5 m) (Qiu and Xie, 1998). Basal area is 91 m^2 ha^{-1}, leaf area index (LAI) varies from 4.8 to 6.5 through the year and tree density is 2728 individuals ha^{-1} (Schaefer *et al.*, 2009). The forest ecosystem is free of management with a stand age >300 years (Tan *et al.*, 2011). This mountain forest is characterized by shortage of growing season warmth and high solar radiation (Fang *et al.*, 1996; Qiu and Xie, 1998; Gao *et al.*, 2009). The soil is loamy clay, with soil volumetric water content rarely falling below 35% in the upper 50 cm (Gong *et al.*, 2011).

In an area without forest cover, a standard meteorological observation station (open land) was established in 1981. The shortest distance between this station and the forest edge was about 200 m. Another meteorological station was established under the forest canopy without disturbing the forest structure. The shortest distance from the under forest canopy meteorological station to the forest edge was about 300 m. Both of these meteorological stations are at the same altitude and similar aspects (Figure 1). In the recent three decades, no tree mortality or gap-forming events have taken place near the understory meteorological station. Stable litterfall shows that the LAI in this study site has been constant at least since 1991 (Liu *et al.*, 2002; Eriksson *et al.*, 2005; Schaefer *et al.*, 2009).

2.2. Meteorological observations

In this study, we utilized temperature observations in open land (1983–2010) and under forest canopy (1986–2010). Air and soil temperature observations, in both settings, followed procedures of the China Meteorological Administration. Air temperature (T_{a}) was measured with a mercury thermometer inside a standard radiation shelter at 1.5 m height. Soil temperatures (T_{s}) were measured by bent stem mercury thermometers at depths of 0, 5, 10, 15 and 20 cm (abbreviated as T_{s}_0,

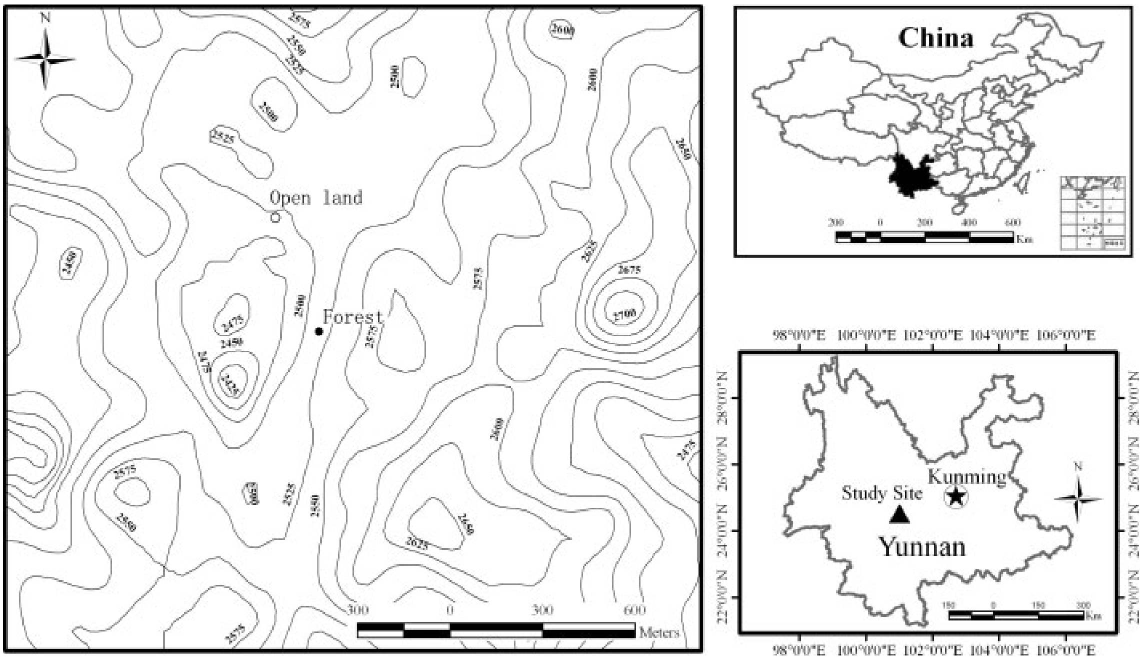

Figure 1. Location of the study site and the topography of the meteorological stations of open land (open land) and under forest canopy (forest).

T_s_5, T_s_10, T_s_15 and T_s_20, respectively). Thermometers located at 0 cm were placed on the mineral soil surface in open land and on the organic layer under the forest canopy. Litterfall on the thermometer under forest canopy was periodically removed to keep the surface thermometer exposed to the air. Daily mean temperatures were averaged from measurements at 02 : 00, 08 : 00, 14 : 00 and 20 : 00 China time. Monthly mean temperature is averaged from those daily mean temperatures. Seasonal temperatures were averaged over three months (Spring is March to May, Summer is June to August, Autumn is September to November and Winter is December to the next February). Throughout the measurement periods, equipment, procedures and sampling locations have not been changed.

For relationship of the T_a and T_s trends, sunshine hours (S_t) and wind speed (W_s) records in open land meteorological station were used for correlation analysis. S_t was observed by dark-tube sunshine hour recorder. China Meteorological Administration (2003) provided the detailed descriptions of instrument and measurement. W_s was recorded at 10 m height. Daily W_s were averages from observations at 08 : 00, 14 : 00 and 20 : 00 China time. Monthly mean S_t and W_s were averaged from those daily values.

2.3. Radiation budgets in open land and under forest canopy

To explore the radiation budgets of open land and under forest canopy, we took advantage of the automatic recording meteorological observation system (located in the open land). Global radiation (Q) and reflective radiation (Q_a) were recorded by CM11 (Kipp & Zonen, Delft, The Netherlands). Net radiation (R_n) was measured by CNR1 (Kipp & Zonen, Delft, The Netherlands). Soil heat flux (G) was measured with HFP01 (Hukseflux, Delft, The Netherlands).

We made four (January, April, July and October) short-term micrometeorological campaigns in the under forest canopy area. Each observation continued for 11 or more days (12 d in January, 17 d in April, 11 d in July and 12 d in October). Net radiation (R_n), together with downward/upward short/long wave radiation, was measured by CNR1 (Kipp & Zonen, Delft, The Netherlands), and soil heat flux (G) was measured by HFP01 (Hukseflux, Delft, The Netherlands). Simultaneous measurements showed that the ratios of daily Q to downward short wave radiation were 1.055 ($n = 30$, $R^2 = 0.983$) in January, 1.057 ($n = 30$, $R^2 = 0.986$) in April, 1.144 ($n = 30$, $R^2 = 0.991$) in July and 1.069 ($n = 30$, $R^2 = 0.952$) in October. Q and Q_a under forest canopy were computed by the measured downward/upward short wave radiation and the coefficients of each month. Effective radiation (I) was computed by subtracting Q_a and R_n from Q. Downward radiation components were defined as positive, and upward radiation components were defined as negative.

2.4. Trend analysis

Trends in air and soil temperatures were analysed with the Mann–Kendall test (Mann, 1945; Hamed, 2008). Mann–Kendall's *tau* values and their significances were calculated by the 'Kendall'package (McLeod, 2009) in the R environment (R Development Core Team, 2010). Positive *tau* values indicated an increasing trend.

Serial autocorrelation could influence the trend significance detected by Mann–Kendall test (von Storch, 1995). A pre-whitening procedure (MK-TFPW) was applied here to reduce the influence of autocorrelation on the significance of Mann–Kendall test results (Yue *et al.*, 2002). Then, the Mann–Kendall test was applied to pre-whitened temperature series.

Long-term trends are computed by simple linear regression (SLR) $y = a_1 t + a_0$, where t is the time (season/years), y is the temperature in season/year and a_1 is the slope of temperature trend.

To clarify the relationship between soil and air temperature, these temperature series were standardized to dimensionless indices (Equation 1, Equation 2). Using AnClim software (Štěpánek, 2008), ten years low-pass-filter lines were built for the dimensionless time series. To reveal any abrupt changes in the temperature series, we built a soil–air temperature difference series. The Mann–Whitney–Pettit test was conducted on the soil–air temperature difference series (Pettitt, 1979). The Mann–Whitney–Pettit test was calculated with AnClim software (Štěpánek, 2008).

$$\hat{Y}_i = (Y_i - \overline{Y})/\sqrt{(Y_i - \overline{Y})^2/n} \tag{1}$$

$$\overline{Y} = \frac{1}{n}\sum_{k=1}^{n} Y_k \tag{2}$$

Y_i is air/soil temperature series. $\overline{Y}$ is the averaged value of air/soil temperature series.

3. Results

3.1. Microclimatic difference between open land and under forest canopy

Table I lists the daytime and night-time radiation budgets. During daytime, understory Q was <5% of Q in open land (3.1% in January, 4.1% in April, 3.7% in July and 2.3% in October). Daytime T_a and T_s_0 in open land were much higher than those under forest canopy; however, their differences are small at night, especially for T_a in these two sites. Correlation analysis on daily records showed that Q in open land had significant correlation with T_s_0 ($P < 0.05$), wind speed had significant correlations with the difference between T_s_0 and T_a ($P < 0.001$) in open land and T_s_0 difference between open land and under forest canopy had weak correlation with the concurrent wind speed ($P < 0.1$).

Long-term averages of T_a and T_s_0, both in the open land and under forest canopy, showed unimodal patterns

Table I. Comparison of radiation components (MJ m^{-2} d^{-1}) and temperatures (°C) between open land and under forest canopy.

		Open land				Forest			
		January	April	July	October	January	April	July	October
Daytime	Q	9.76 ± 1.87	19.55 ± 1.83	10.71 ± 1.37	8.71 ± 1.74	0.27 ± 0.06	0.85 ± 0.10	0.43 ± 0.17	0.15 ± 0.02
	Q_a	−2.04 ± 0.38	−3.66 ± 0.33	−2.12 ± 0.24	−1.79 ± 0.36	−0.07 ± 0.02	−0.17 ± 0.02	−0.05 ± 0.01	−0.03 ± 0.00
	I	−2.66 ± 0.57	−4.85 ± 0.44	−3.36 ± 1.19	−2.43 ± 0.47	−0.08 ± 0.06	0.07 ± 0.02	−0.05 ± 0.02	0.03 ± 0.04
	R_n	5.06 ± 0.99	10.08 ± 1.50	5.18 ± 1.07	5.25 ± 1.19	0.11 ± 0.04	0.71 ± 0.08	0.15 ± 0.05	0.13 ± 0.04
	G	0.48 ± 0.17	0.85 ± 0.16	0.89 ± 0.21	0.72 ± 0.20	−0.11 ± 0.04	0.13 ± 0.02	0.11 ± 0.04	−0.07 ± 0.04
	T_a	5.14 ± 0.62	15.74 ± 0.69	16.18 ± 0.45	11.18 ± 0.36	4.02 ± 0.45	13.54 ± 0.52	14.35 ± 0.24	9.92 ± 0.48
	T_s_0	9.48 ± 0.79	20.40 ± 0.96	20.37 ± 0.63	14.51 ± 0.29	4.33 ± 0.24	12.40 ± 0.28	12.77 ± 0.19	12.97 ± 0.02
Night-time	I	−1.21 ± 0.31	−1.75 ± 0.15	−0.75 ± 0.10	−1.22 ± 0.33	−0.12 ± 0.02	−0.02 ± 0.02	−0.05 ± 0.00	−0.12 ± 0.03
	G	−0.70 ± 0.10	−0.94 ± 0.07	−0.71 ± 0.05	−0.77 ± 0.15	−0.23 ± 0.03	−0.10 ± 0.02	−0.09 ± 0.01	−0.21 ± 0.06
	T_a	3.46 ± 0.61	11.00 ± 0.44	14.15 ± 0.21	8.21 ± 1.13	3.60 ± 0.37	11.69 ± 0.36	13.90 ± 0.21	8.99 ± 0.85
	T_s_0	5.67 ± 0.51	12.72 ± 0.26	17.18 ± 0.27	10.90 ± 0.77	4.25 ± 0.25	11.73 ± 0.24	13.84 ± 0.19	12.97 ± 0.02

Daily average and standard error were computed by short-term observations in each season (12 d in January, 17 d in April, 11 d in July, 12 d in October). Daytime is the period of 7 : 00–19 : 00 local time, and night-time is the rest of the period in the days.

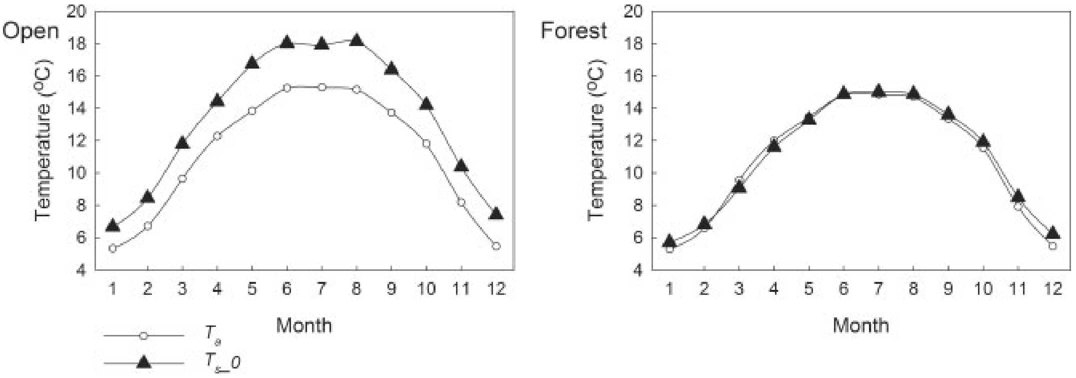

Figure 2. The average annual variation of T_a and T_s_0 in open land (Open, data from 1983 to 2010) and under forest canopy (Forest, data from 1986 to 2010). ○, T_a; ▲, T_s_0.

of annual variation (Figure 2). In the open land, average T_s_0 was 2.3 °C higher than T_a, and T_s_0 was 0.2 °C higher than T_a under forest canopy. Further, T_s_0 in the open land was 2.4 °C higher than that under the forest canopy. Average soil temperatures increased with depth with a rate of 0.17 °C per 10 cm in open land and 0.07 °C per 10 cm under forest canopy.

3.2. Air/soil temperature trends in both sites

As the time series of T_a and T_s at all depths had low serial autocorrelations, the Mann–Kendall trend test of pre-whitened series showed similar results to the original Mann–Kendall trend test (Table II). Both open land and under forest canopy showed significant positive trends in T_a. T_s at all depths had significant positive trends under forest canopy. In open land, T_s trends of all depths were positive, but trends in T_s_0, T_s_5 and T_s_10 were insignificant and trends in T_s_15, T_s_20 were significant.

Mean annual T_a increased more rapidly than that of T_s in open land, and the T_a increase was higher in the open land (0.36 °C/decade) than under forest canopy (0.27 °C/decade). However, the annual mean T_s_0 slightly increased in the open land (0.07 °C/decade), which was much less than that under the forest canopy (0.24 °C/decade). T_s increases at all depths under forest canopy were nearly double those in the open land. Both T_a and T_s at all depths showed higher increases in winter than in other seasons (Table II).

3.3. Different response between soil temperature and air temperature

Figure 3 shows the standardized temperature series of open land T_a and T_s_0 in each season and the whole year. Low-pass filtered and standardized T_a series was similar to T_s_0 in spring and winter. In summer and autumn, however, this standardized T_s_0 has responded differently than that of T_a. The Mann–Whitney–Pettit test showed that the year of 1998 was a change point in the soil–air temperature difference series ($P < 0.05$), which suggests that T_s_0 has responded differently than T_a since that year.

Correlation analysis of long-term data sets showed significant positive correlations between S_t and T_s_0 and between W_s and T_a (Table III). Deceleration of S_t was seen after 1998 and W_s showed stable significant positive trends both before and after 1998 (Table IV).

4. Discussion

4.1. Microclimates in open land and under forest canopy

This study shows that limited energy reached the ground under the forest canopy. Part of the radiation would

Table II. Trend analysis of T_a and T_s at all depths in both open land and under forest canopy with 'MK test original', 'TFPW MK test' and 'SLR' means the *tau* value, the *tau* value with pre-whitened transformation and simple linear regression model, respectively.

	Open land			Under forest canopy		
	MK test Original *tau*	TFPW MK *tau*	a_1 (SLR) and 95% confidence interval (°C/decade)	MK test Original *tau*	TFPW MK *tau*	a_1 (SLR) and 95% confidence interval (°C/decade)
T_a	0.25*	0.23*	0.24* (−0.03, 0.52)	0.15	0.19	0.20 (−0.13, 0.52)
T_s_0	0.09	0.07	0.11 (−0.34, 0.55)	0.18	0.22	0.22 (−0.05, 0.50)
T_s_5	0.02	0.03	0.12 (−0.26, 0.469)	0.26*	0.25*	0.22* (−0.05, 0.50)
Spring						
T_s_10	−0.03	−0.01	0.07 (−0.30, 0.45)	0.40***	0.41***	0.34** (0.07, 0.60)
T_s_15	0.03	0.06	0.16 (−0.22, 0.54)	0.32**	0.31**	0.26* (−0.01, 0.53)
T_s_20	0.08	0.09	0.22 (−0.20, 0.64)	0.24*	0.24*	0.20 (−0.07, 0.48)
T_a	0.49***	0.50***	0.21*** (0.11, 0.31)	0.26*	0.55***	0.13** (0.01, 0.25)
T_s_0	−0.02	0.08	0.09 (−0.12, 0.39)	0.24*	0.33**	0.13** (0.01, 0.25)
T_s_5	0.06	0.11	0.03 (−0.04, 0.30)	0.16	0.22	0.09 (−0.06, 0.24)
Summer						
T_s_10	0.02	0.04	−0.01 (−0.19, 0.18)	0.34**	0.26*	0.16** (0.04, 0.28)
T_s_15	0.02	−0.04	0.01 (−0.17, 0.19)	0.24*	0.25*	0.12* (−0.02, 0.25)
T_s_20	0.12	−0.02	0.05 (−0.13, 0.24)	0.14	0.06	0.08 (−0.07, 0.22)
T_a	0.31**	0.43***	0.33** (0.08, 0.58)	0.18	0.38***	0.23 (−0.07, 0.52)
T_s_0	−0.12	−0.13	−0.09 (−0.42, 0.25)	0.22	0.22	0.26* (−0.02, 0.55)
T_s_5	0.04	0.04	0.07 (−0.24, 0.38)	0.33**	0.37**	0.32** (0.07, 0.58)
Autumn						
T_s_10	−0.03	−0.05	0.05 (−0.22, 0.32)	0.37**	0.38***	0.33*** (0.10, 0.57)
T_s_15	0.09	0.08	0.08 (−0.17, 0.34)	0.34**	0.22	0.33** (0.08, 0.59)
T_s_20	0.08	0.07	0.09 (−0.18, 0.37)	0.43***	0.32**	0.43*** (0.12, 0.74)
T_a	0.44***	0.59***	0.63*** (0.26, 1.00)	0.41***	0.43***	0.55** (0.13, 0.97)
T_s_0	0.11	0.03	0.16 (−0.29, 0.61)	0.26*	0.18	0.33 (−0.07, 0.74)
T_s_5	0.32**	0.32**	0.32* (0.03, 0.67)	0.40***	0.27*	0.47** (0.12, 0.82)
Winter						
T_s_10	0.27**	0.20	0.30* (−0.04, 0.64)	0.37**	0.26*	0.41** (0.07, 0.74)
T_s_15	0.23*	0.16	0.33* (−0.03, 0.68)	0.30**	0.22	0.38** (0.03, 0.74)
T_s_20	0.20	0.14	0.33* (−0.04, 0.71)	0.28*	0.35**	0.46** (0.03, 0.89)
T_a	0.48***	0.45***	0.36*** (0.18, 0.53)	0.39***	0.44***	0.27*** (0.08, 0.47)

Table II. (*Continued*).

		Open land			Under forest canopy		
		MK test Original *tau*	TFPW MK *tau*	a_1 (SLR) and 95% confidence interval (°C/decade)	MK test Original *tau*	TFPW MK *tau*	a_1 (SLR) and 95% confidence interval (°C/decade)
Year	T_s_0	0.10	0.18	0.07 (−0.18, 0.31)	0.34^{**}	0.20	0.24^{**} (0.05, 0.43)
	T_s_5	0.22	0.21	0013^{**} (0.08, 0.35)	0.39^{***}	0.22	0.28^{***} (0.09, 0.46)
	T_s_10	0.19	0.19	0.10 (−0.10, 0.31)	0.47^{***}	0.32^{**}	0.31^{***} (0.14, 0.48)
	T_s_15	0.25^{*}	0.23^{*}	0.15 (−0.05, 0.34)	0.43^{***}	0.29^{**}	0.27^{***} (0.10, 0.44)
	T_s_20	0.25^{*}	0.24^{*}	0.17^{*} (−0.03, 0.38)	0.40^{***}	0.28^{*}	0.29^{***} (0.10, 0.49)

***, two sides significance <0.01; **, two sides significance <0.05; *, two sides significance <0.1.

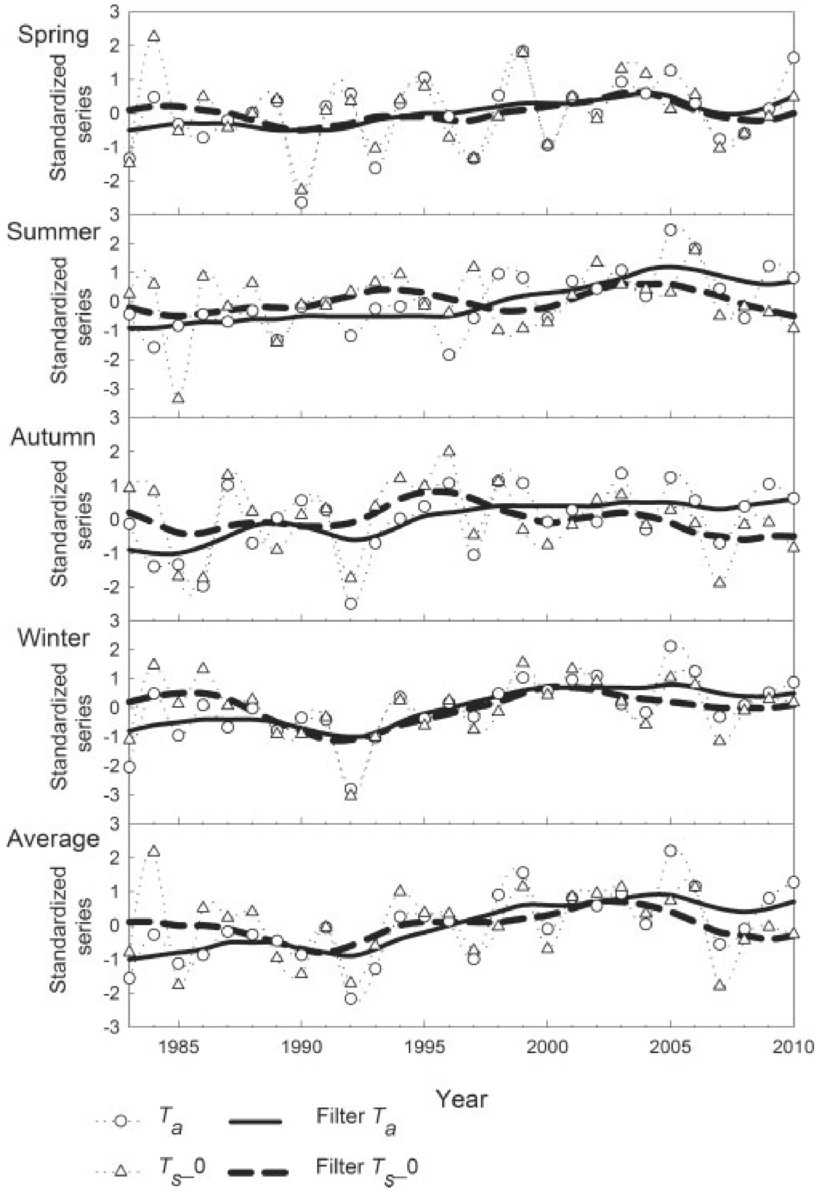

Figure 3. Standardized time series of T_a and T_s_0 in each season and the whole year (average) of open land. Thin dotted lines were the standardized time series of T_a (open circle) and T_s (open triangle). Bold lines were ten-year low-pass filter of T_a (solid line) and T_s (dashed line). ○, T_a; △, T_s_0.

Table III. Pearson correlation analysis on the standardized time series of T_a, T_s_0 and their difference (T_s_0 − T_a) with standardized S_t and W_s.

Standardized variables		Open land			Under forest canopy		
		T_a	T_s_0	T_s_0 − T_a	T_a	T_s_0	T_s_0 − T_a
Spring	S_t	0.434^{**}	0.334	0.106	0.404^{*}	0.392^{*}	−0.174
	W_s	0.188	−0.030	−0.252	−0.003	−0.080	−0.299
Summer	S_t	0.141	0.576^{***}	0.506^{**}	−0.045	−0.143	−0.266
	W_s	0.176	0.042	−0.031	0.024	−0.071	−0.269
Autumn	S_t	−0.033	0.184	0.236	0.038	0.011	−0.092
	W_s	0.223	−0.213	-0.453^{**}	0.241	0.243	0.029
Winter	S_t	0.424^{**}	0.321	−0.163	0.270	0.173	−0.233
	W_s	0.516^{**}	−0.021	-0.704^{***}	0.135	−0.072	-0.501^{**}
Average	S_t	0.180	0.392^{*}	0.259	−0.022	0.000	0.116
	W_s	0.398^{*}	−0.118	-0.533^{***}	0.061	−0.007	−0.295

***, two sides significance <0.01; **, two sides significance <0.05; *, two sides significance <0.1.

Table IV. Linear trends of T_a, T_s_0, S_t and W_s in before-1998 (Bf), after-1998 (Af) and the entire periods (1983–2010).

	S_t (h·10^{-1})		W_s (m ·s^{-1}·10a^{-1})		T_a(°C·10a^{-1})	T_s_0 (°C·10a^{-1})
	Bf/Af	1983–2010	Bf/Af	1983–2010	Bf/Af	Bf/Af
Spring	22.02/4.68	1.06	$1.20^{*}/0.93^{***}$	0.50^{***}	0.09/−0.10	−0.39/−0.45
Summer	7.58/−0.55	5.99	$0.88^{**}/1.28^{***}$	0.35^{**}	0.03/0.07	0.44/0.13
Autumn	25.54/12.21	6.25	$1.04^{***}/1.11^{***}$	0.40^{***}	0.34/−0.10	0.41/−0.57
Winter	5.88/19.00	10.98^{**}	$1.28^{***}/1.22^{***}$	0.65^{***}	0.26/−0.19	−0.74/−0.68
Average	15.25/8.83	6.07	$1.10^{***}/1.14^{***}$	0.48^{***}	0.18/−0.08	−0.07/−0.39

***, two sides significance <0.01; **, two sides significance <0.05; *, two sides significance <0.1.

have been absorbed by vegetation and transferred to water vapour instead of temperature increase. Therefore, daytime understory T_s_0 was substantially lower than that of open land. During night-time, decrease in understory T_s_0 was greatly lower than that of open land, as a result of forest canopy limiting heat loss (Table I). Consequently, forest canopy has strong effect on the temperature extremes (Renaud and Rebetez, 2009; Ferrez *et al.*, 2011). However, the impact of forest cover on mean temperature could not be entirely explained by the limitation of radiation (Renaud and Rebetez, 2009). Soil temperature below the forest canopy could be more influenced by air temperature and wind speed (Carlson and Groot, 1997; Morecroft *et al.*, 1998; Paul *et al.*, 2004). In this study, nocturnal T_a in open land was close to that of understory (Table I), indicating sufficient heat exchange and a strong effect of wind advection (Renaud and Rebetez, 2009). Owing to high heat capacity of soil, daily understory T_s_0 did not respond as rapidly as did T_a. Therefore, the correlation significance between wind speed and difference of T_s_0 in open land and under forest canopy was low ($P < 0.1$). However, monthly data showed that understory T_s_0 was closely correlated with T_a in open land with a linear regression coefficient of 1.02 (n = 300, $R^2 = 0.977$) for open land T_a to understory T_s_0. We conclude that T_s_0 in open land is sensitive to Q, and wind speed plays important roles in open land T_a and understory T_s_0.

4.2. T_a and T_s trends in open land

This study showed that T_a and T_s at all depths have increased more in winter than in other seasons. Strong winter warming has also been observed elsewhere in south-west China (Liu and Chen, 2000; Fan *et al.*, 2010; Qin *et al.*, 2010). As winter S_t had significant correlation with T_a and T_s_0 (Table III), strong winter warming in this study could be attributed to the stronger increase of winter S_t (Table IV). This positive trend of S_t was also observed in rural and mountainous areas of the Yunnan-Guizhou Plateau (Zheng *et al.*, 2010).

Correlation analysis showed that T_a and T_s_0 were more influenced by W_s and S_t, respectively. The role of turbulence on T_a was confirmed by a significant negative correlation between W_s and the soil–air temperature difference (Table III). Consequently, changes in S_t and W_s could separately influence trends in T_s_0 and T_a. This study revealed a stable increase in W_s, which agrees with a previous report by Jiang *et al.* (2010). However, the trend in S_t has decelerated after 1998 (Table IV). Consequently, T_s_0 has responded differently than T_a since that year (Figure 3). This change point agrees with You *et al.* (2010) who reported a sharp decrease of S_t and increase of total cloudiness at the end of the 1990s. As a whole, compared with long-term averages, W_s has increased 4.9% and S_t has increased 1.6% in these recent 30 years. Therefore, change of T_a (and the closely correlated understory T_s_0) is greater than open land T_s_0.

As soil temperature and air temperature may have been driven separately, no conclusion has been made on the global pattern of trends in air temperature and soil temperature. A higher trend of soil temperature than air temperature has been reported in Northern Ireland (García-Suárez and Butler, 2006). Also, soil temperature in south-west China and East Tibetan Plateau slightly decreased from 1954 to 2001 (Lu *et al.*, 2006), which contradicted with the slightly increase of air temperature (Liu *et al.*, 2004). The increase S_t in this study only reflects an increase in duration of sunshine hours above the threshold of 120 W m^{-2}; the amplitude of solar radiation could not be observed in our S_t records. Accordingly, increased S_t recorded by the dark-tube sunshine hour recorder implies an increased frequency of cloud-free days (Qian *et al.*, 2006), and any increase in aerosols and their influence on solar radiation could not be seen in our S_t. Trend in soil temperature is considered to be correlated with changes in solar radiation (Jacobs *et al.*, 2011). As a result, the lower trend of T_s_0 compared with T_a in open land could be considered as an indicator of decreased solar radiation, possibly from increased atmospheric aerosols (Alpert and Kishcha, 2008; Alpert *et al.*, 2005; Liu *et al.*, 2004; Qian *et al.*, 2006).

5. Implication

This study reveals an increasing trend of 0.36 °C/decade in T_a, which is double the previous reported trends in our regional temperatures (Liu and Chen, 2000; He and Zhang, 2005; Wan *et al.*, 2009; Fan *et al.*, 2010). A higher temperature trend is consistent with a high sensitivity of mountain areas to climate change (Beniston, 2003; Shrestha and Aryal, 2011). As a result, the distribution of mountain forests, which is considered to be limited by temperature (Fang *et al.*, 1996), could be displaced upward. However, stronger winter warming in this study suggests an enhanced aridity in winter; increased temperature and sunshine hours could strengthen evaporative water demand. Consequently, the impact of changes in temperature and aridity on the ecological and biological perspective of mountain forests needs to be addressed.

Strong canopy effects on the understory micrometeorology were revealed in this study. As a result, T_s at all depths in open land were higher than those under forest canopy (Figure 2). Higher soil temperatures in open land could be important for seed germination and thus forest restoration. Trends of understory T_s at all depths were higher than those of open land. As a result of close relation between soil temperature and soil respiration (Jones *et al.*, 2006), warming effects on soil respiration could be underestimated if predictions are based on meteorological observations in open land.

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References

Alpert P, Kishcha P. 2008. Quantification of the effect of urbanization on solar dimming. *Geophysical Research Letters* **35**: L08801, DOI: 10.1029/2007GL033012.

Alpert P, Kishcha P, Kaufman YJ, Schwarzbard R. 2005. Global dimming or local dimming?: Effect of urbanization on sunlight availability. *Geophysical Research Letters* **32**: L17802, DOI: 10.1029/2005GL023320.

Beniston M. 2003. Climatic change in mountain regions: A review of possible impacts. *Climatic Change* **59**(1–2): 5–31, DOI: 10.1023/A:1024458411589.

Bond-Lamberty B, Thomson A. 2010. Temperature-associated increases in the global soil respiration record. *Nature* **464**(7288): 579–582, DOI: 10.1038/Nature08930.

Carlson DW, Groot A. 1997. Microclimate of clear-cut, forest interior, and small openings in trembling aspen forest. *Agricultural and Forest Meteorology* **87**(4): 313–329, DOI: 10.1016/S0168-1923 (95)02305-4.

China Meteorological Administration. 2003. *Specifications for Surface Meteorological Observation*. Meteorological Press: Beijing, 81–82.

Eriksson H, Eklundh L, Hall K, Lindroth A. 2005. Estimating LAI in deciduous forest stands. *Agricultural and Forest Meteorology* **129**(1–2): 27–37, DOI: 10.1016/j.agrformet.2004.12.003.

Fan ZX, Bräuning A, Thomas A, Li JB, Cao KF. 2011. Spatial and temporal temperature trends on the Yunnan Plateau (Southwest China) during 1961–2004. *International Journal of Climatology* **31**(14): 2078–2090, DOI: 10.1002/joc.2214.

Fang JY, Ohsawa M, Kira T. 1996. Vertical vegetation zones along 30 degrees N latitude in humid East Asia. *Vegetatio* **126**(2): 135–149, DOI: 10.1007/BF00045600.

Ferrez J, Davison A, Rebetez M. 2011. Extreme temperature analysis under forest cover compared to an open field. *Agricultural and Forest Meteorology* **151**(7): 992–1001, DOI: 10.1016/j.agrformet.2011.03.005.

Gao JB, Zhang YP, Gong HD, Liu YH. 2009. Characteristics of solar radiation of subtropical broad-leaved forest area in Ailao Mountains, Southwest China [in Chinese with English abstract]. *Journal of Mountain Science* **27**(1): 33–40.

García-Suárez A, Butler C. 2006. Soil temperatures at Armagh Observatory, Northern Ireland, from 1904 to 2002. *International Journal of Climatology* **26**(8): 1075–1089, DOI: 10.1002/joc.1294.

Gong HD, Zhang YP, Lei YB, Liu YH, Yang GP, Lu ZY. 2011. Evergreen broad-leaved forest improves soil water status compared with tea tree plantation in Ailao Mountains, Southwest China. *Acta Agriculturae Scandinavica Section B-Soil and Plant Science* **61**(4): 384–388, DOI: 10.1080/09064710.2010.494615.

Hamed KH. 2008. Trend detection in hydrologic data: The Mann-Kendall trend test under the scaling hypothesis. *Journal of Hydrology* **349**(3–4): 350–363, DOI: 10.1016/j.jhydrol.2007.11.009.

He YL, Zhang YP. 2005. Climate change from 1960 to 2000 in the Lancang River valley, China. *Mountain Research and Development* **25**: 341–348, DOI: 10.1659/0276-4741(2005)025[0341:CCFTIT]2.0.CO;2.

IPCC. 2007. Summary for policymakers. In *Climate Change 2007: The Physical Science Basis, Contribution of working group I to the Forth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, New York, 1–18.

Jacobs AFG, Heusinkveld BG, Holtslag AAM. 2011. Long-term record and analysis of soil temperatures and soil heat fluxes in a grassland area, The Netherlands. *Agricultural and Forest Meteorology* **151**: 774–780, DOI: 10.1016/j.agrformet.2011.01.002.

Jiang Y, Luo Y, Zhao ZC, Tao SW. 2010. Changes in wind speed over China during 1956–2004. *Theoretical and Applied Climatology* **99**(3–4): 421–430, DOI: 10.1007/s00704-009-0152-7.

Jones CD, Cox PM, Huntingford C. 2006. Climate-carbon cycle feedbacks under stabilization: Uncertainty and observational constraints. *Tellus Series B-Chemical and Physical Meteorology* **58**(5): 603–613, DOI: 10.1111/j.1600-0889.2006.00215.x.

Körner C, Paulsen J. 2004. A world-wide study of high altitude treeline temperatures. *Global Change Biology* **31**: 713–732, DOI: 10.1111/j.1365–2699.2003.01043.x.

Liu BH, Xu M, Henderson M, Qi Y, Li YQ. 2004. Taking China's temperature: Daily range, warming trends, and regional variations, 1955–2000. *Journal of Climate* **17**(22): 4453–4462, DOI: 10.1175/3230.1.

Liu WY, Fox JED, Xu ZF. 2002. Litterfall and nutrient dynamics in a montane moist evergreen broad-leaved forest in Ailao Mountains, SW China. *Plant Ecology* **164**: 157–170, DOI: 10.1023/A:1021201012950.

Liu XD, Chen BD. 2000. Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology* **20**(14): 1729–1742, DOI: 10.1002/1097-0088(20001130)20:14<1729::AID-JOC556>3.0.CO;2-Y.

Lu XB, Xu HM, Sun CH, He JH. 2006. Characteristics of soil temperature variations in China in recent 50 years [in Chinese with English abstract]. *Journal of Nanjing Institute of Meteorology* **29**(5): 706–712.

Mann HB. 1945. Nonparametric tests against trend. *Econometrica* **13**(3): 245–259.

McLeod AI. 2009. *Kendall: Kendall Rank Correlation and Mann-Kendall Trend Test*. R package version 2.1. http://CRAN.R-project.org/package=Kendall.

Morecroft MD, Taylor ME, Oliver HR. 1998. Air and soil microclimates of deciduous woodland compared to an open site. *Agricultural and Forest Meteorology* **90**(1–2): 141–156, DOI: 10.1016/S0168-1923(97)00070-1.

Paul KI, Polglase PJ, Smethurst PJ, O'Connell AM, Carlyle CJ, Khanna PK. 2004. Soil temperature under forests: A simple model for predicting soil temperature under a range of forest types. *Agricultural and Forest Meteorology* **121**(3–4): 167–182, DOI: 10.1016/j.agrformet.2003.08.030.

Pettitt AN. 1979. A non-parametric approach to the change-point problem. *Applied Statistics* **28**(2): 126–135.

Qian Y, Kaiser DP, Leung LR, Xu M. 2006. More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000. *Geophysical Research Letters* **33**(1): L01812, DOI: 10.1029/2005gl024586.

Qin NX, Chen Xi, Fu GB, Zhai JQ, Xue XW. 2010. Precipitation and temperature trends for the Southwest China: 1960–2007. *Hydrological Processes* **24**: 3733–3744, DOI: 10.1002/hyp.7792.

Qiu XZ, Xie SC. 1998. *Studies on the Forest Ecosystem in Ailao Mountains Yunnan,China*. Yunnan Science and Technology Press: Kunming, China.

R Development Core Team. 2010. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing: Vienna, Austria. ISBN 3-900051-07-0.

Renaud V, Rebetez M. 2009. Comparison between open-site and below-canopy climatic conditions in Switzerland during the exceptionally hot summer of 2003. *Agricultural and Forest Meteorology* **149**(5): 873–880, DOI: 10.1016/j.agrformet.2008.11.006.

Schaefer DA, Feng WT, Zou XM. 2009. Plant carbon inputs and environmental factors strongly affect soil respiration in a subtropical forest of southwestern China. *Soil Biology and Biochemistry* **41**(5): 1000–1007, DOI: 10.1016/j.soilbio.2008.11.015.

Shrestha AB, Aryal R. 2011. Climate change in Nepal and its impact on Himalayan glaciers. *Regional Environmental Change* **11**: S65–S77, DOI: 10.1007/s10113-010-0174-9.

Štěpánek P. 2008. *AnClim – Software for Time Series Analysis (for Windows)*. Dept. of Geography, Fac. of Natural Sciences, Masaryk University, Brno. 1.47 MB. http://www.climahom.eu/AnClim.html.

Subedi M, Fullen MA. 2009. Temporal changes in soil temperature at the Hilton experimental site, Shropshire, UK (1982–2006): Evidence of a warming trend? *Archives of Agronomy and Soil Science* **55**(1): 105–113, DOI: 10.1080/03650340802343159.

Tan ZH, Zhang YP, Schaefer D, Yu GY, Liang NS, Song QH. 2011. An old-growth subtropical Asian evergreen forest as a large carbon sink. *Atmospheric Environment* **45**(8): 1548–1554, DOI: 10.1016/j.atmosenv.2010.12.041.

von Storch H. 1995. Misuses of statistical analysis in climate research. In *Analysis of Climate Variability Applications of Statistical Techniques*, von Storch H and Navarra A (eds). Springer: New York.

Wan YX, Zhang WC, Xiao ZN. 2009. Spatiotemporal variation characteristics of air temperature in Longitudinal Ridge-gorge Region of Yunnan in recent century [in Chinese with English abstract]. *Journal of Natural Disasters* **18**(5): 183–188.

You Q, Kang S, Flügel WA, Sanchez-Lorenzo A, Yan Y, Huang J, Martin-Vide J. 2010. From brightening to dimming in sunshine duration over the eastern and central Tibetan Plateau (1961–2005). *Theoretical and Applied Climatology* **101**(3): 445–457, DOI: 10.1007/s00704-009-0231-9.

Yue S, Pilon P, Phinney B, Cavadias G. 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes* **16**(9): 1807–1829, DOI: 10.1002/hyp.1095.

Zheng XB, Luo YX, Duan CC, Zhao TL, Chen J, Kang WM. 2010. Change trends and causes in sunshine duration and visibility over Yunnan-Guizhou plateau in recent 45 years [in Chinese with English abstract]. *Plateau Meteorology* **29**(4): 992–998.