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Microclimatic Conditions for *Juniperus saltuaria* Treeline in the Sygera Mountains, Southeastern Tibetan Plateau

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*Although the southeastern Tibetan Plateau has one of the world's highest natural treelines, little is known about its microclimatic conditions. In order to characterize microclimatic conditions for natural Blackseed juniper (*Juniperus saltuaria *[Rehd & Wils], syn:* Sabina saltuaria*) treeline (4390 masl) in the Sygera (Sergyemla) Mountains, southeastern Tibetan Plateau, an in situ field measurement based on an automatic weather station (AWS) has been running since November 2006. The annual mean air temperature ranged from 0 to 0.8°C from 2007–2009. The mean air temperature for the warmest month (July) was 7.9 ± 0.5°C, while mean air temperatures during the growing season were 6.8 ± 0.3°C (Index 1) and 6.2 ± 0.2°C (Index 2, corresponding to the global scale), based on a definition of the growing season according to a daily mean air temperature of >5°C and soil temperature at 10 cm depth >3.2°C. However, the mean soil temperature at a depth of 10 cm during the growing season (8.0 ± 0.2°C) was higher than that measured for the global treelines. The juniper treeline is characterized by a humid microclimate, as shown by the mean daily relative humidity of 76.4%, annual total precipitation of 871.3 mm, and mean soil volumetric moisture content of 35.5% during periods when the soil is not frozen. The annual mean wind speed was 0.9 ± 0.1 m/s. Uninterrupted in situ micrometeorological field measurements for alpine treelines should be the next step to achieve a better understanding of treeline ecological conditions and treeline formation on the Tibetan Plateau.*

Keywords: Juniperus saltuaria*; treeline; microclimate; Sygera Mountains; southeastern Tibetan Plateau; China.*

Peer-reviewed: *December 2010* ***Accepted:*** *January 2011*

Introduction

The upper altitudinal limit of forest on high mountains, commonly referred to as treeline or timberline (see the schematic representation in figure 1 in Körner and Paulsen 2004), is likely to be one of the first forested ecosystems to register climate impacts in terms of changes in structure and position (Grace et al 2002; Holtmeier 2003; Körner 2003; Broll and Keplin 2005; Wieser and Tausz 2007; Harsch et al 2009; Smith et al 2009). One of the world's highest natural treelines is found on the southeastern Tibetan Plateau (Miehe et al 2007). There is a considerable need in research focusing on treelines or timberlines, such as the recent dendroecological studies in the Sygera Mountains on the southeastern Tibetan (Liang et al 2009, 2010, 2011), for better understanding of the microclimate of local treelines. By comparison with the European Alps, Subarctic North America, and northern Europe (Holtmeier 2003; Körner 2003), little is known about micrometeorological conditions at the treelines or timberlines on the Tibetan Plateau (Li BS 1993; Li WH 1993; Cui et al 2005; Schickhoff 2005; Li et al 2008; He et al 2009; Liu and Luo 2011).

As for the treeline/timberline environmental studies, Holtmeier (2003) emphasized that one of the problems is the use of climate records from valley floors or lowlands to predict climatic variables such as precipitation at higher elevations. In particular, difficulties increase when applying local results to the alpine treelines of distant mountain ranges on the Tibetan Plateau (Miehe and Miehe 2000). Unfortunately, few uninterrupted in situ micrometeorological field measurements are available for the high-elevation treelines, primarily due to poor access and bad weather conditions throughout the year on the southeastern Tibetan Plateau, where almost all the meteorological stations are located at lower altitudes on the floor of the river valley. Limited knowledge of the treeline microclimate on the southeastern Tibetan Plateau to date has been based on short-term observations of soil temperature and moisture (Shi et al 2008; He et al 2009; Liu and Luo 2011).

To better understand the microclimatic conditions of the treeline on the southeastern Tibetan Plateau, we set up an automatic weather station (AWS) on topography exposed to the sun on the eastern side of the Sygera (Sergyemla) Mountains. The objective of this study was to

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FIGURE 1 (A) Map showing the site of the AWS at the treeline of Blackseed juniper forest in the Sygera Mountains in Nyingchi (Linzhi) County on the southeastern Tibetan Plateau, and location of the study area within China (inset). (B) View of the Blackseed juniper treeline. In the Sygera Mountains, the grass grows better close to the river valley, from 3550 to 3850 masl. No grass is available for yak grazing at the treeline ecotone due to the high coverage of rhododendron shrubs; nor did we see any summer grazing at our study site. (Map by Hua Tian; photo by Eryuan Liang, 27 October 2007)

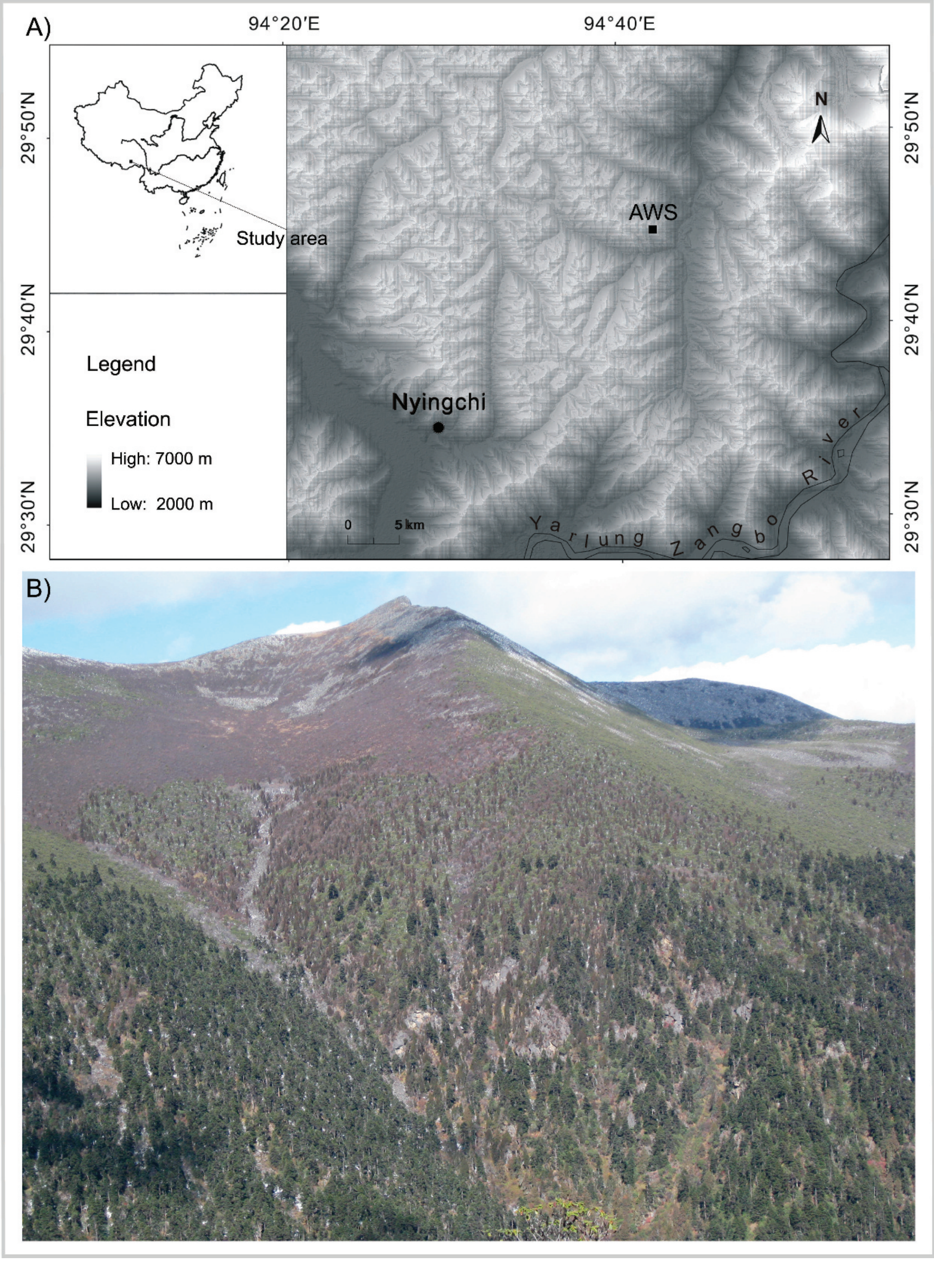

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TABLE 1 Descriptions of meteorological parameters and sensors used in this study.

Parameter	Sensor	Accuracy	Position
Incoming solar radiation	LI200X pyranometer	± 3 to 5%	3 m height
Air temperature	HMP45C-L temperature	± 0.4°C	3 m height
Relative humidity	Relative humidity probe	± 2% (0 to 90%)	3 m height
		± 3% (90 to 100%)	
Soil temperature	107 temperature probe	± 0.1°C	10, 20, 40 cm depth
Soil volumetric moisture content	CS616 water content reflectometer	± 2.5%	10, 20, 40 cm depth
Precipitation	TE525M tipping bucket rain gauge	0.1 mm	1 m height
Wind speed and direction	05103 R. M. Yong wind monitor	± 0.5 ms^{-1}; ± 5°	3 m height
Aerometric pressure	CS100 barometric pressure sensor	± 1.5 mb	1 m height
Ultrasonic snow depth	SR50 sonic ranging sensor	± 1 cm	3 m height

characterize micrometeorological conditions of Blackseed juniper (*Juniperus saltuaria* [Rehd & Wils], syn: *Sabina saltuaria*) treeline based on AWS measurements from 1 December 2006 to 28 February 2010.

Material and methods

The study site is located in Nyingchi area on the eastern side of the Sygera Mountains (29°10′–30°15′N, 93°12′–95°35′E), a transition zone between semihumid and humid climates in southern Tibet, China (Figure 1A). The South Asian monsoon reaches the Sygera Mountains along the Yarlung Zangbo River, resulting in abundant summer monsoon rainfall. Funded by several agencies in China, a Tibetan Observation and Research Platform (TORP) is now focusing on land-surface processes and environment over the Tibetan Plateau (Ma et al 2008). The Southeast Tibet Station for Alpine Environmental Observation and Research of the Institute of Tibetan Plateau Research of the Chinese Academy of Sciences, established in August 2005, is one of the stations focusing research on the alpine environment on the southeastern Tibetan Plateau.

In our study area, Blackseed juniper grows along an altitudinal gradient from 4200 to 4400 m on the slope exposed to the south. It forms a natural altitudinal treeline (7–8 m in height, coverage less than 20%) around 4400 m (Figure 1B). Shrubs, such as *Rhododendron aganniphum* var *vellerum*, *Rhododendron nyingchiense, Cassiope fastigiata*, *Potentilla parvifolia,* and *Rubus stans*, dominate the understory layers at the treeline ecotone. Smith fir (*Abies georgei* var *smithii*) dominates the lower subalpine forests from around 3600 m, close to the river valley floor, to 4200 m. Podzol soil, characterized by an ash-gray horizon bleached by organic acids underneath the humus layer, is dominant at the treeline ecotone.

On 5 November 2006, we set up an AWS at a selected site (29°39.420′N, 94°42.427′E, 4390 m, slope angle around 10°) just above the treeline of Blackseed juniper forest on a 2 × 2 m^2 plot where there was no vegetation cover. The AWS is a model CR1000 (Campbell Scientific). A summary of the sensors and measurements is given in Table 1. All sensors collected data at 30-minute intervals, Beijing Standard Time, in order to compare with other AWS measurements within the Tibetan Observation and Research Platform. We analyzed the records from 1 December 2006 to 28 February 2010. An average of the 48 half-hour dataset was considered to be the daily mean. The daily data (maximum, minimum, mean) were then averaged to obtain monthly values. Seasonal (winter: December–February; summer: June–August) and annual means were calculated from the monthly data.

The daily mean air and soil temperatures were frequently used to determine the beginning and the end of the growing season (Körner and Paulsen 2004; Walther and Linderholm 2006). In order to make a reasonable comparison between treelines, 2 methods were used to define the growing season, based on the mean daily air temperature and soil temperature at a depth of 10 cm, recorded by the treeline AWS. The growing season was defined as the following:

1. The period between the mean daily temperature >5°C in spring and <5°C in autumn for at least 5 consecutive days (Walther and Linderholm 2006); and
2. The interval at which the soil temperatures at 10 cm exceeded 3.2°C in spring and dropped below 3.2°C for the first time in autumn (Körner and Paulsen 2004).

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Results

General description

At the Blackseed juniper treeline, the average daily barometric pressure was 601.9 hPa, being about 59.4% of that at sea level (1013 hPa). Annual short-wave radiation totals amounted to 4457 MJ/m^2, with the maximum radiation in May and June (Figure 2A). In the last 3 years, the highest monthly value (487 MJ/m^2) occurred in May 2007. It is difficult to compare our results with those obtained for other alpine treelines because solar radiation is closely related to site conditions (Barry 1981; Holtmeier 2003; Körner 2003).

Air temperature

Annual mean air temperature at the treeline was 0.6, 0.0, and 0.8°C in 2007, 2008, and 2009, respectively. The highest air temperatures occurred in July or August, and the lowest air temperatures occurred in January or February (Figures 2B, 3). The mean temperatures in summer (June–August) were 7.0, 6.8, and 7.5°C in 2007, 2008, and 2009, respectively. The mean air temperature for the warmest month (July) in the last 3 years was 7.9 ± 0.5°C, with an extreme high daily mean air temperature of 10.5°C (on 13 July 2009). The mean temperature for the coldest month (February) in the last 3 years was −7.1 ± 2.1°C, with an extreme low value of −14.3°C (on 1 February 2008).

Based on the 2 definitions of the growing season according to daily air temperatures (>5°C) and soil temperatures at a depth of 10 cm (>3.2°C), the lengths of the growing seasons were 119 ± 6 and 149 ± 9 days, respectively (Table 2). The mean air temperatures during the growing seasons were 6.8 ± 0.3 and 6.2 ± 0.2°C, respectively.

Relative air humidity and precipitation

The juniper treeline is characterized by a humid climate. Average daily relative air humidity was 76.4%, with the highest monthly value being 87.2 ± 3.3% in August and the lowest 62.8% in December (Figures 2A, 3). During the growing season the mean relative air humidity was above 84% (Table 2).

Mean annual precipitation was around 871.3 mm for the past 3 years, with peak values occurring in June, July, and August (148, 168, and 139 mm, respectively), accounting for 52% of annual precipitation (Figures 2C, 3). Influenced by the onset of the Indian summer monsoon, precipitation showed large interannual variability. Annual total precipitation was 882, 960, and 754 mm in 2007, 2008, and 2009, of which summer precipitation was 484, 491, and 391 mm, respectively. Cooler summers tended to be associated with more precipitation. Extreme precipitation events were also frequent, such as daily precipitation of 48.8 and 37.2 mm on 17 August 2008 and 4 July 2008, respectively.

Snowfall mainly ranged from November to May at the juniper treeline and is a particularly important moisture source given its seasonal dominance. As observed, the snow cover ranged from 22 October 2007 to 25 May 2008 (217 days) and from 27 October 2008 to 29 April 2009 (185 days). It was heavier in early 2008, with a snow cover of 0.63 m on 30 March 2008 (Figure 2C). Considering the great spatial variability of snow distribution at the high altitude, we should emphasize that the snowfall records refer to the AWS stand.

Soil temperature

The annual mean soil temperatures (2.63, 2.59, and 2.74°C at 10, 20, and 40 cm, respectively) were higher than the annual mean air temperatures mentioned above. The variations in soil temperatures at 10 cm were similar but lagged behind variations in air temperatures by 4–8 hours (Figure 4A). For example, daily air temperature reached a maximum at 15:00 h on 12 June 2008, while the soil temperature peaked at 18:30 (12 June 2008), 0:30 (13 June 2008), and 5:30 h (13 June 2008) at depths of 10, 20, and 40 cm, respectively. As observed, under snow cover, the soil temperatures generally do not drop far below zero at the treeline ecotone (Holtmeier 2003). The mean soil temperature at 10 cm during the growing season (>3.2°C) was 8.0 ± 0.2°C. During later winter and early spring, the soil temperature measured under the snow was quite stable (about 0°C); however, the air temperature varied abruptly. Snowmelt produced a sharp thermal signal, and soil temperatures could exceed 5°C within 2 or 3 days (Figures 2B, 4B). Variations (estimated as the standard deviation, SD) in the mean soil temperatures decreased in amplitude with soil depth (Figure 4C). Moreover, the SD of the monthly mean soil temperatures was highest in May, June, and October and was different from that for the monthly air temperatures, whose variations were greatest in winter (Figure 4C).

Soil volumetric moisture content

Following snowmelt and increasing precipitation, soil moisture increased rapidly from the beginning of April and remained higher from May to August. In late September, soil moisture began to decrease with decreasing precipitation, and in late November and early December soil freezing appeared below a depth of 40 cm (Figure 2D). Average soil moisture during the periods when soil was not frozen decreased with depth, being 35.5, 32, and 14.6% at 10, 20, and 40 cm, respectively. During the last 3 years, the extreme high value was 52.3% at 10 cm, as recorded on 11 August 2007. The soil moisture was above 30% for almost half a year, from 2 May to 24 November in 2007, 27 May to 30 November in 2008, and 3 May to 30 October in 2009, which was much longer than the growing seasons (Table 2).

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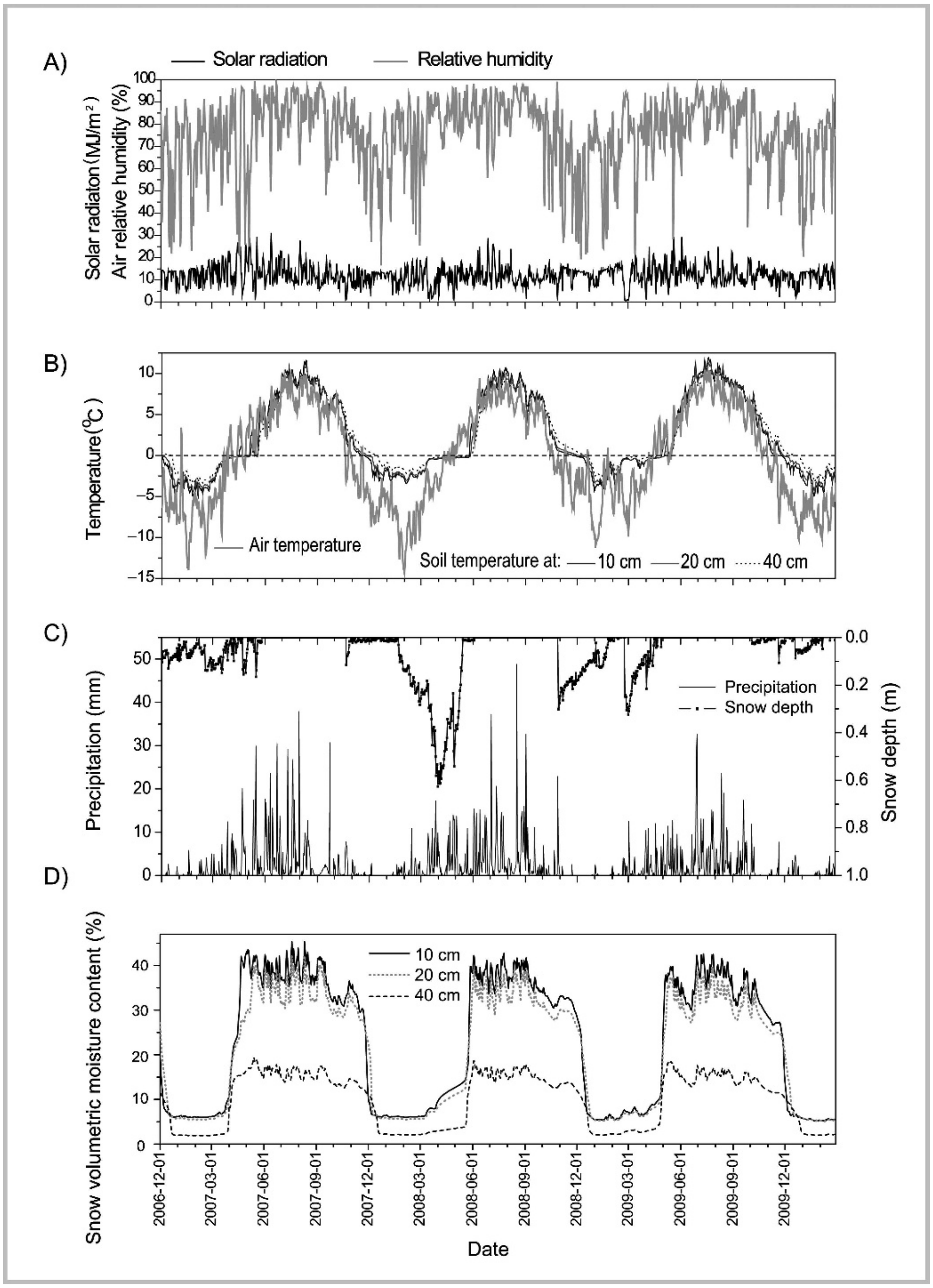
FIGURE 2 (A) Variations in daily incoming solar radiation and daily average relative humidity; (B) daily mean air temperature and daily soil temperature (at depths of 10, 20, and 40 cm); (C) daily total precipitation and daily total snow depth; (D) daily mean soil volumetric moisture contents at depths of 10, 20, and 40 cm.



Wind velocity and direction

At our treeline site, the prevailing winds were from SSE (south-southeast), SE (southeast), and S (south), accounting for 54% of the annual wind direction frequencies (Figure 5A). The wind from WNW (west-northwest) and NW (northwest) became stronger in January, and the wind from S was stronger in July (Figure 5A). The mean annual wind speed was 0.9 ± 0.1 m/s. The wind was stronger during the daylight hours in January and before midnight in July. The lowest values appeared mainly between 8:00 and 11:00 h within a day (Figure 5B).

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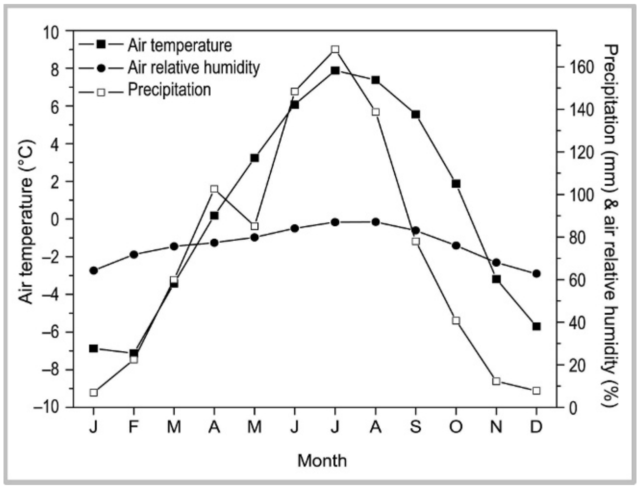
FIGURE 3 Monthly mean air temperatures, relative humidity, and monthly precipitation based on the AWS records at the Blackseed juniper treeline on the eastern side of the Sygera Mountains.



the findings of Li WH (1993) and Frenzel et al (2003), who gave a figure of 8°C for the warmest month at the treelines on the southeastern Tibetan Plateau. It was also within the scale for the warmest month (between 7.6 and 8.7°C) for the treelines in southeast Tibet, Yunnan, and Sichuan, as calculated by Schickhoff (2005). However, it was lower than the 10°C isotherm for the warmest month, which is a coincidence of the treeline position in the northern hemisphere (Holtmeier 2003) and a mean (9.7°C) derived from the treelines across northeastern and western China (Wang et al 2004). In addition, it seems to be lower than that at the same latitude (Körner 2003) and in high-altitude spruce-fir forests (13–14°C) in 3 major mountain ranges of the northeastern United States (Richardson et al 2004).

Winter temperatures at the treeline of Blackseed juniper were not lower in comparison with others in the Northern Hemisphere. As reported, winter temperatures below −40°C are not uncommon in the Northern Hemisphere (Zwiazek et al 2001). For European Alpine treelines, the minimum air temperature can drop to −36°C during winter (Neuner 2007).

However, we should be cautious about comparisons of treeline temperatures because early studies of treelines were based on interpolation of temperature data from meteorological stations at lower altitudes far away from the treelines. In these cases air temperatures at treelines were generally estimated by using a certain lapse rate with elevation (Tranquillini 1979; Li WH 1993; Liu et al 2002; Frenzel et al 2003; Wang et al 2004). In addition, the length of the growing season length is largely dependent on

Discussion

Air and soil temperatures

Alpine treeline is generally characterized by a harsh environment, and its existence is considered to be primarily related to heat deficiency (Holtmeier 2003; Körner 2003). The mean air temperatures for the growing season and the warmest month (usually July) were commonly used to describe the treeline position. The mean air temperature during the growing season was within the global scale (5.5~7.5°C; Körner 2003). At our treeline site, July temperature (7.9 ± 0.5°C) was roughly in agreement with

TABLE 2 Microclimatic conditions during the growing season from 2007 to 2009 at the Blackseed juniper treeline. The growing season was defined as Index 1 (the period between the mean daily temperature >5°C in spring and <5°C in autumn for at least 5 consecutive days) and Index 2 (the interval at which the soil temperatures at 10 cm exceeded 3.2°C in spring and dropped below 3.2°C for the first time in autumn).

Index for growing season	Year	Duration of growing season/length	Air temperature (°C)	Air relative humidity (%)	Total precipitation (mm)	Soil temperature at 10 cm (°C)	Soil moisture at 10 cm (%)
1	2007	16 Jun–7 Oct (114 days)	6.9	84.5	421.0	8.7	38.1
	2008	8 Jun–4 Oct (119 days)	6.5	86.3	540.5	8.4	37.8
	2009	5 Jun–8 Oct (125 days)	7.1	84.0	481.7	9.1	36.3
	Average	119 ± 5.5 days	6.8 ± 0.3	84.9 ± 1.2	481.1 ± 59.8	8.7 ± 0.4	37.4 ± 1.0
2	2007	21 May–20 Oct (153 days)	6.3	84.6	571.6	7.9	37.7
	2008	28 May–13 Oct (139 days)	6.0	85.4	602.8	7.8	37.6
	2009	20 May–22 Oct (156 days)	6.3	82.4	521.9	8.2	35.9
	Average	149 ± 9.1 days	6.2 ± 0.2	84.1 ± 1.6	565.4 ± 40.8	8.0 ± 0.2	37.1 ± 1.0

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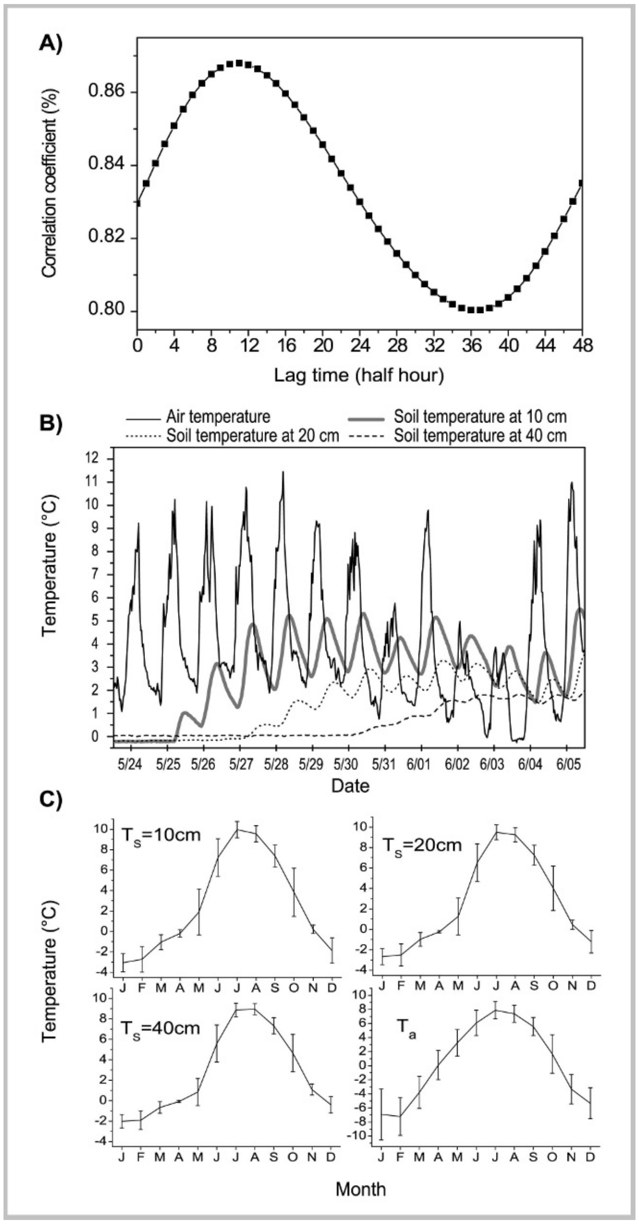
FIGURE 4 (A) Correlation coefficients between the air and soil temperatures at 10 cm; (B) air and soil temperature patterns during the thawing of the seasonal frozen layer in 2008; (C) the monthly mean air (T_a) and soil temperatures (T_s). (Error bars are ± one standard deviation).



topographical aspects (Tang and Fang 2006; Liu and Luo 2011), leading to difficulties in comparing data from different treeline areas.

In general, the roots of seedlings distribute in the upper 10 to 20 cm of the soil. Temperature within the rooting zone was considered to be a decisive factor in plant growth and survival (Körner 2003; Körner and Paulsen 2004). On a worldwide scale, the upper limit of tree growth and the position of treelines in humid mountains were found to be best correlated with a mean soil temperature of 6.7 ± 0.8°C during the growing season (Körner and Paulsen 2004). The soil temperature at a depth of 10 cm during the growing season at our site was higher than the global mean temperature at treelines (Körner and Paulsen 2004). In the western Sygera Mountains, Liu and Luo (2011) reported that slope aspect and vegetation variables rather than altitude were the major determining factors for spatial variability of seasonal mean soil temperatures. A higher soil temperature may be related to the selection of the AWS site where there is no vegetation cover. We noted that the mean soil temperature for the growing season at a depth of 10 cm at our sites was close to that for the alpine grassland and low shrub above the treeline of Blackseed juniper (Liu and Luo 2011).

Relative air humidity, precipitation, and soil moisture

The treeline of Blackseed juniper is characterized by a humid microclimate, as shown by the records of the relative air humidity, precipitation, and soil moisture. Annual precipitation of 871.3 mm at our treeline sites is on the scale of precipitation (800 to 2600 mm at a mesoscale) for treelines in the European Alps (Wieser and Tausz 2007) but seems to be lower than precipitation at 3850 m on the same slope close to the river valley in the Sygera Mountains (Wang et al 2002). Long-lasting snow cover and high soil moisture due to meltwater keep the soil temperature low until early summer or even longer (Holtmeier 2003). In our case the heavy snow in early 2008 delayed the onset of the growing season, as defined by the daily mean soil temperatures at a depth of 10 cm.

The period with soil moisture above 30% was much longer than the growing season. Net photosynthesis starts to decline when soil moisture is below 30% volume (Havranek and Benecke 1978). Considering that juniper is the most drought-tolerant species among treeline-forming tree species (Holtmeier 2003), soil moisture may not be a direct limiting factor for Blackseed juniper growth and development at the treeline in the Sygera Mountains. Across various mountains all over the world, Körner (2003) also concluded that soil moisture is unlikely to exert major direct physiological limitations on alpine plant life.

Wind velocity and direction

As already noted, knowledge of the influence of wind on site conditions at the treeline on the Tibetan Plateau is very deficient (Schickhoff 2005). At the treeline site, the wind velocity and direction may be strong, depending on site conditions and dense *Rhododendron* shrubs at the treeline ecotone. Similar to our observations, Barry (1981) also noted that wind velocity is not as strong as expected in some of the highest mountains in the subtropics and the inner parts of larger mountains. By comparison, the mean annual wind speed was much lower at our site than in the European Alps or in the Rocky Mountains (ranging between 7 and more than 10 m/s; Holtmeier 2003). As this is a diffuse treeline, there are no flag Blackseed juniper trees at the treeline ecotone and above the treeline;

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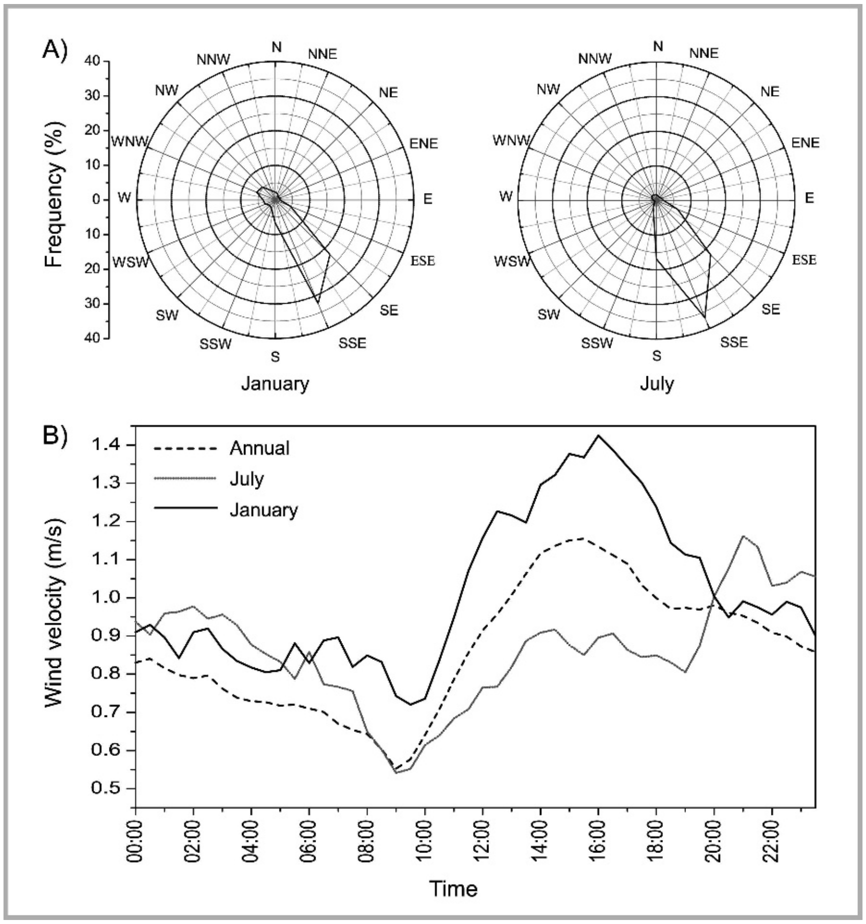
FIGURE 5 (A) Frequency distributions of wind directions in January and July; (B) the diurnal variation of wind velocity at the Blackseed juniper treeline.



therefore, it does not seem that wind is an important factor in treeline formation of Blackseed juniper in the Sygera Mountains.

Conclusion

This paper presents the results of an in situ monitoring of several microclimatic parameters in order to better understand treeline ecological conditions on the Tibetan Plateau. The treeline of Blackseed juniper in the Sygera Mountains is characterized by a humid microclimate, with high precipitation, relative air humidity, and soil moisture. The mean air temperature during the growing seasons is on the scale of that (ranging from 5.5 to 7.5°C) derived from global treelines. The mean air temperature of the warmest month was slightly lower than that at the same latitude. However, the mean soil temperature at a depth of 10 cm during the growing season was higher than that found across the global treelines. Because of the great variety and heterogeneity of alpine treelines, treeline micrometeorological records of Blackseed juniper in the Sygera Mountains cannot be considered to be representatives of alpine treelines on the Tibetan Plateau. To show a clearer picture of the alpine treeline environment on the southeastern Tibetan Plateau, long-term in situ microclimate monitoring of the treelines across different species and along the altitudinal gradients of tree species will be necessary.

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