Two Phases of Seasonal Stem Radius Variations of *Sabina przewalskii* Kom. in Arid Northwestern China Inferred from Sub-Daily Shrinkage and Expansion Patterns

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Abstract

To enhance the understanding of the dynamics of tree-ring growth during the year, we investigated stem radius variations of six Qilian juniper (*Sabina przewalskii* Kom.) trees using high-resolution dendrometer measurements taken at the Sidalong Forestry Station in the Qilian Mountains National Nature Reserve of China. The seasonal stem radius variations were divided into two phases because of different sub-daily shrinkage and expansion patterns. When associated to climatic parameters, the boundaries of the two phases corresponded with the occurrence of 0 °C mean air temperature.We found that *phase 1* in 2010 and 2011, respectively, was most appropriate to eventually performed growth and climate relationships in this cold and arid region as these periods likely implied the whole season of stem radius increase. From the long-term trend of stem radius variations, May to August could be deduced as the main radial growth period, which corresponded with high air temperature and heavy precipitation in 2010 and 2011. The use of sub-daily shrinkage and expansion patterns method thus provides deeper insight into stem radius growth activities.

Keywords Dendrometers, sub-daily shrinkage and expansion patterns, *Sabina przewalskii* Kom., Qilian Mountains

Introduction

The understanding of tree growth processes is at the basis of dendroclimatology in order to reconstruct past climatic history (Fritts 1976). Traditionally, scientists did not pay attention to tree species located in cold and arid regions because they have very significant seasonal rhythms. The Qilian Mountains region, located in the middle latitude arid areas in northwestern China, is one of the most sensitive areas to global climate change. The species Qilian juniper (*Sabina przewalskii* Kom.) growing in this region is a long-lived species that has been used to develop the longest known chronology in China (Shao et al., 2010). However, there are still debates about the relationships between tree rings and climate, even within the same research areas. Although several studies, such as Liu et al. (2005) and Liu et al. (2006), found that temperature had a positive effect on Qilian juniper annual growth, standard dendroclimatological analyses carried out in the same regions showed that tree-ring width had consistent effects related to precipitation but not to temperature (Zhang and Wu 1997; Kang et al. 2003; Qin et al. 2010; Yang et al. 2010; Yang et al. 2011; Yang et al. 2012). These reconstructions were based on the correlations between tree-ring width and observed meteorological data, and did not consider the actual physiological mechanisms due to lack of understanding of dynamics of tree-ring growth.

A more detailed approach based on intra-annual monitoring of tree-growth and meteorological dynamics could considerably refine our understanding of these conflicting results in this important environment. Use of automated precision dendrometers is a traditional standard method to measure stem radius variation (Fritts 1962; Deslauriers et al. 2007; Drew and Downes 2009) with high precision. It can provide continuous monitoring of stem radial variations throughout the year, which is crucial for understanding the tree’s reaction to short-term changes in environmental conditions such as temperature, soil water content, and rainfall (Deslauriers et al. 2007).

Due to the reversible stem shrinking and swelling, dendrometers have been criticized when used to measure short-term growth rates (Zweifel and Häsler 2001; Mäkinen et al. 2003). Nevertheless, in the past decade high-precision dendrometers have been used in different tree species and environments to describe stem radius growth phenology and/or assess growth – climate relationships in: *Tabebuia chrysantha* (Volland-Voigt et al. 2009; Volland-Voigt et al. 2011), *Podocarpus falcatus, Pinus patula, Prunus Africana,* and *Celtis africana* (Krepkowski et al. 2010), *Pinus hartwegii* (Biondi and Hartsough 2010; Biondi et al. 2005), ten species such as *Cedrela* cf. *Montana* and *Clethra revoluta* (Bräuning et al. 2008; Bräuning et al. 2009) in tropical mountain forest, *Pinus sylvestris* (Oberhuber and Gruber 2010) in dry inner Alpine valley, *Picea mariana* (Deslauriers et al. 2007; Turcotte et al. 2009) in boreal forest and *Picea abies* (Bouriaud et al. 2005) in temperate forest, *Fitzroya cupressoides, Nothofagus nitida* and *Podocarpus nubigena* (Pérez et al. 2009) in temperate montane coastal rainforests, *P. violacea* and *C. mopane* (February et al. 2007) in sub-tropical arid savanna, and even clones of *Populus* in botany research (Giovannelli et al. 2007). Qilian juniper is one of the slow-growing species in cold and arid environment. And in traditional dendroclimatology research, tree-ring width of Qilian juniper was thought to be more narrow than other species (eg: Qinghai spruce) in the same areas.

However, there were still no studies on Qilian juniper to assess the stem growth dynamics, which is, because of its reduced growth, the first step to identify the seasonal periods of stem variation during the year before performing any growth and climate relationships. Understanding the dynamics of stem radius growth would help for past climate history reconstruction in arid northwestern China in order to develop a prospect to solve reconstruction disagreement in traditional dendroclimatology in this region. Therefore, due to extreme and rhythmic environmental conditions influencing tree growth, the seasonal stem radius variations can be divided in different phases as stem radius change may have different physiological response mechanisms to climatic factors (Turcotte et al. 2009).

We used two-year data series to (1) determine whether dendrometer measurements were suitable to monitor slow-growing tree species in a cold and arid environment, and (2) to determine the timing of the different phases related with stem radius variations patterns during the year.

Materials and Methods

Study area

The investigation was undertaken in the Sidalong Forestry Station of the Qilian Mountains National Natural Reserve. The study area was located on the north slope of the middle Qilian Mountains in northwestern China (Fig. 1). The site represent a mountainous virgin forest with abundant vegetation dominated by Qilian juniper (*Juniperus przewalskii* Kom.) on sunny slopes and Qinghai spruce (*Picea crassifolia* Kom.) on cloudy slopes (Fig. 2). The study area is located in the upper section of the Heihe River, deep in the hinterland of the Qilian Mountains with extremely difficult vehicle access, so there is no human interference with the tree growth environment except for a few herdsmen occasionally looking for their livestock. Our research site is in the Qilian juniper pure forest with little shrubs of *Caragana jubata*, *Dasiphora fruticosa* and *Nitraria sibirica* on the sunny slopes, and the soil was classified as a mountain brown forest soil type with an average pH value of 7.5 (Yang et al. 2008).

The climate of the region is continental with cold winters and warm summers, and may be sensitive to variations in the strength of different atmospheric circulation patterns because of its proximity with the northwestern boundary of the Asian summer monsoon (Yang et al. 2010). According to the meteorological station Qilian (38.11°′ N, 100.15°′ E, 2,787 m a.s.l.) close to the study area, the mean January and July temperatures are -13.13 and 13.02 °C, respectively. Mean annual precipitation amounts 403.29 mm for the period 1957 – 2007. The precipitation from May to September occupy 89.97% of the annual total (Fig. 3).

Dendrometer measurements

To study short-term stem radius variations, high-resolution point and band dendrometers (Ecomatik, Germany; type DR and DC2, accuracy ±2 μm, temperature coefficient ＜0.1 μm/K) were installed in 2010 at heights ranging from 0.5 to 1.5 m above ground on six Qilian junipers which were healthy and upright, with circumference ranging from 36 to 85 cm. To reduce the influence of expansion and shrinkage processes in the bark, some parts of the outer bark were removed without wounding the cambial zone. Stem radius variations of the six studied trees were automatically registered each 30-min intervals and saved in dendrometer data loggers (Ecomatik, Germany). Due to technical problems, the measurements of the four trees did not started on the same date; therefore, to compare the differences of stem radius change rhythm between different altitudes, four of the trees were measured at the lower limit (LL) and the other two at the middle location (ML) of the forest (Table 1).

The daily maximum values of stem radius variations were calculated from dendrometer raw data and were used to delineate the common and different characteristics among the six studied trees. As the dendrometer type DC2 measured stem circumference change, the average stem radius variations of LL2 and ML2 trees were transformed to radius values by dividing the values obtained by 2π. The daily amplitudes of stem radial changes were calculated as the differences between the daily maximum and the minimum values. Also, the exact appearance times of the daily extreme values (maximum and minimum) were computed as a frequency distribution among the daily hours (from 0:00 to 23:30) to gain deeper insight into the sub-daily shrinkage and expansion patterns of stem radius change.

Microclimate records

A 2-m-high automated weather station was installed at an exposed and flat space in LL (38°26.27′ N, 99°55′ E, 2,859 m a.s.l.). Level distances were less than 50 m from the station to LL1, LL2, LL3 and LL4. Several environmental parameters (precipitation, air temperature, soil temperature, soil water content [at 20 and 40 cm underground, respectively], relative humidity, barometric pressure, solar radiation, and photosynthetic active radiation) were automatically measured at one-hour intervals and stored in a data logger (Delta-T Devices Ltd, U.K., Type DL2e) beginning on March 6 in 2010. The daily precipitation records between the LL weather station and the Xiang Yangtai meteorological station (38°26.79′ N, 99°53.87′ E, 2,670 m a.s.l.) were compared to test the accuracy of the LL weather station. A high consistency between the two series was found. However, from March 7 to October 27 in 2010, the sum of precipitation at LL was 407.40 mm, higher than the Xiang Yangtai Station records (364.60 mm), which may suggest an altitudinal effect on precipitation in this area.

Results

Sub-daily stem radius variations: The hypothesis of 'two phases'

To gain deeper insight into the sub-daily stem radius variations, we calculated the daily maximum and minimum values distribution frequency in local daily hours from 0:00 to 23:30 at 30-min intervals (Fig. 4). Figure 4 presents the frequency distribution of the daily min and max over the whole measurement periods for the six sample trees. The black horizontal lines represent the mean distribution frequency to every hour point. Above these black lines, the six trees each revealed a distinct bimodal shape. The daily max and min values both appeared in the morning and afternoon except at LL1. LL1 has the longest measurement period including the whole season of stem radius growth in two years. Due to the long winter period of dendrometer measurement, the frequency distribution of LL2, LL3, LL4, ML1 and ML2 showed that stem shrinkage and expansion patterns are different to LL1, reach the daily maximum both in the afternoon and in the next morning. The beginnings and ends of days, corresponding with 0:00 and 23:30, respectively, also contained a certain proportion of the extreme values distribution.

Temporal point diagrams of the sub-daily shrinkage and expansion patterns were presented in order to illustrate the timing of expansion and contraction over two years (Fig. 5). The red dots represent the timing of daily maximum values, representing the end of expansion, and the blue triangles represent daily minimum values, representing the end of stem contraction. In LL1, period during late April to October in 2010, sub-daily data indicate marked regular patterns of daily maximum values occurring in the morning and minimum values in the afternoon. However, from the end of October to March in 2011, the shrinkage and expansion patterns completely inversed: the daily maximums appear in the afternoon while daily minimums appear in the morning. During the end of March to early November in 2011, the sub-daily shrinkage and expansion patterns inversed again. According to these patterns, several time intervals were defined and correspond with *phase 1* from April 27 to October 23 in 2010 and from March 29 to November 3 in 2011, respectively; *phase 2* from October 24 in 2010 to March 28 in 2011. *Phase 1* generally revealed maximum values in the morning and minimum values in the afternoon; and *phase 2* showed abnormal patterns with maximums observed in the afternoon and minimums observed in the morning.

The other five trees (LL2, LL3, LL4, ML1 and ML2 in Fig. 5) displayed basically the same sub-daily patterns, and the partition of each phase consistently began from the same date, similar to

LL1. Despite the consistent trends of the six trees, there are slight differences in the sub-daily shrinkage and expansion patterns.

Seasonal stem radius variations

Over two years, stem radius variations of the six sample trees display synchronism in the observed pattern (Fig. 6a, b). *Phase 1* corresponds with the continuous and steady ascending trend until the end of this period, and *phase 2* demonstrates a drastic decreasing trend in the early part and increasing trend in the late part of stem radius variations.

For more detailed comparisons among the six trees, daily amplitudes were calculated (Fig. 7). To some degree, the daily amplitudes indicated the extent of stem radius change: lower daily amplitudes represent gentle change while higher daily amplitudes reveal drastic change. Compared with other five trees, the daily amplitudes of LL1 were lower than the others, the maximum values were about 300 μm, while LL2 and ML1 had higher values in the range of 500 μm. Compared with *phase 2*, the daily amplitudes of all trees in *phase 1* revealed more moderate patterns. Meanwhile, the highest and the lowest daily amplitudes were concentrated in *phase 2*, respectively. Both in the early part and late part of *phase 2,* daily amplitudes revealed abnormally high values, while in the middle part (from December 5 in 2010 to February 2 in 2011), all of the sample trees' daily amplitudes presented negligible values.

Correspondence between stem radius variations and the two phases

To assess the correspondence between stem radius variations and climatic factors, the climatic parameters of the two phases were compared with Figure 6a, b. The daily maximum, minimum, and mean air temperature, relative humidity, precipitation, soil temperature and soil water content (20 cm and 40 cm below ground, respectively) were presented in Figure 6c, d, e. The dividing lines of the two phases highly corresponded with the 0 °C of the daily mean air temperature. In other words, the mean air temperature increased above 0 °C at the beginning of *phase 1* and the ending of *phase 2*.

From April 27 to October 23 in 2010 (*phase 1*), the mean air temperature was consistently above 0 °C, although on May 17 and October 14, it briefly dropped below 0 °C. This period corresponds with dates of the main rainfall period, in which the total precipitation (343.80 mm) accounted for 83.73 % of the whole measurement in 2010 (410.60 mm). The sub-daily shrinkage and expansion patterns have distinct patterns which agreed with normal view that daily maximums appear in the morning and minimums appear in the afternoon. The measured stem size variations may reflect stem radius growth and water fluctuation; accordingly, stem radius measurements increased about 0.85 mm during this period at LL1, as shown in Figure 6a. The diurnal stem radius changes depend on physiological activities and were not directly sensitive to the temperature course (Fig. 8a). In the early and middle parts of this period (May to August), the stem radius expansion highly corresponded with heavy rain after several days of drying (eg: the stem size showed continuous expansion over 48 hours from May 24 to 26 in figure 8a). However, in the late part of this period (after September), with decreasing daily stem radius amplitudes, daily stem radius variations showed no obvious response to precipitation.

Phase 2 which from October 24 in 2010 to March 28 in 2011 could be divided into three periods according to different daily stem radius amplitudes. In the first period (from October 24 to December 4 in 2010), the daily stem radius amplitudes revealed abnormally high values, the mean air temperature decreased below 0 °C, but the maximum air temperature was above 0 °C until December 4. Precipitation, relative humidity, soil temperature, and soil water content also demonstrated a decreasing tendency. The mean soil temperature (20 cm underground) dropped to below 0 °C until December 3. Stem radius variations revealed a drastic decreasing trend, which was mainly influenced by temperature. The trees exhibited weak physiological activities in this period, when the maximum air and soil temperatures were still above the freezing point (Fig. 8b). This caused the daily stem radius maximum values to not consistently correspond with the maximum air temperature values. The second period was from December 5 to February 2 in 2011. The daily amplitudes of all the sample trees consistently remained at very low levels, revealing that the daily stem radius variations were very limited. From December 5, the maximum air temperature fell below 0 °C and reached its lowest value (– 13.68 °C) on December 15. In the end of this period, the decreasing daily stem radius variations reached its lowest levels, with the dendrometer measurements decreasing about 0.64 mm (LL1), 1.02 mm (LL2), 1.05 mm (LL3), and 1.6 mm (ML1) compared with values on October 24 (the beginning of *phase 2*). The daily stem radius variations may only reflected physical shrinkage and expansion caused by air temperature (Fig. 8c). The sub-daily overall shrinkage and expansion patterns had relatively distinct patterns but there was little distinction between the individual sample trees. In the third period (from February 3 to the end of *phase 2*), the daily amplitudes turn up high levels again, both of air and soil temperature had increasing tendency. As the maximum air temperature increased above 0 °C on February 3 and reached its maximum value at 12.12 °C on March 28, the daily stem radius variations of all the six sample trees were increased rapidly around the same date (Fig. 8d). During only two days (February 3 to 4 in 2011), the stem radius increasing about 0.41 mm (LL1), 0.38 mm (LL2), 0.49 mm

(LL3), 0.42 mm (LL4), 0.78 mm (ML1) and 0.32 mm (ML2).

Phase 1 from March 29 to November 3 in 2011 was similar to *phase 1* in 2010, the mean air temperature was consistently above 0 °C, although it briefly dropped below 0 °C occasionally. Air temperature, relative humidity, soil temperature, and soil water content had rapidly increased in the early part of *phase 1* in 2011. And this period corresponds with dates of the main rainfall date, in which the total precipitation (422.40 mm) accounted for 98 % of the whole measurement in 2011 (431.00 mm). Compared with *phase 2,* the sub-daily shrinkage and expansion patterns in this phase reversed, that daily maximums appear in the morning and minimums appear in the afternoon. The stem radius measurements increased about 0.98 mm (LL1), 3.36 mm (LL2), 1.53 mm (LL3), 2.37 mm (LL4), 1.68 mm (ML1) and 1.65 mm (ML2) during this period as shown in Figure 6a, b. The diurnal stem radius changes depend on physiological activities and were not directly sensitive to the temperature course (Fig. 8e). Compared with *phase 1* in 2010, the *phase 1* in 2011 had longer stem growth period, since the longer duration of the 0 °C mean air temperature in 2011.

Discussion

Illustration of sub-daily shrinkage and expansion patterns

The sub-daily shrinkage and expansion patterns of stem radius variations in trees had been shown in many studies to reach a minimum in mid to late afternoon and a maximum in the early morning, driven by water movement in the tree through the soil-plant-atmosphere interface (see overview, Drew and Downes 2009). Based on the patterns of stem shrinkage and expansion, the daily stem radius variations cycles have been described in terms of either five phases (Herzog et al. 1995) or three phases (Downes et al. 1999; Deslauriers et al. 2003; Deslauriers et al. 2007). In this way the maximum daily variation and increment could be extracted from the dendrometer data each day. The method to define the diurnal changes in stem size had been labeled the *stem cycle approach* by Deslauriers et al. (2007). This method had been used to quantitatively study stem growth dynamics and compare them with other environmental parameters over different species and regions (Downes et al. 1999; Deslauriers et al. 2003; Deslauriers et al. 2007; Krepkowski et al. 2010). This method provided a useful way to calculate relationships between stem radius growth and climatic parameters with dendrometer measurements. However, our study indicated that the sub-daily shrinkage and expansion patterns were not all the same due to seasonal climatic and environmental changes in cold and arid regions. Stem radius variations in *phase 1* consisted of diurnal rhythms of water storage depletion and replenishment and seasonal tree growth. In *phase 1*, stem radius shrinkage was due to transpiration during the daytime, while expansion was due to roots imbibing water from the soil during late afternoon and the night to replenish daytime usage. Therefore, the daily maximums were normally distributed in the morning and the daily minimums were distributed in the afternoon. Certainly, the heavy rain or continuous drought events during growth period could lead to consecutive expansion or shrinkage. Therefore, the daily stem radius variations cycle may lasting more than 24 h, and this could explain the certain proportion of the extreme values distribution at the beginnings (0:00) and ends (23:30) of days in Figure 4 and 5.

During *phase 2*, the daily stem radius changes were mainly influenced by temperature. The differences in air temperature between day and night were the main reason for daily amplitudes of stem radius changes. From late October to early December, the daily maximum temperature was greater than 0 °C and the daily minimum temperature was below – 10 °C; the great differences in daily temperature could explain the abnormally high levels of daily amplitudes of all the sample trees during this period.

Our study agreed with Deslauriers et al.'s (2007) finding in the eastern Italian Alps that the period used for growth and climate analysis should correspond only with the main period of stem growth, excluding the few weeks at the beginning or end of stem radial increase when measurement variability was greater than radial growth. From the sub-daily shrinkage and expansion patterns in our data, we concluded that *phase 1* was most appropriate to analyze stem radius growth relationships with other parameters in this cold and arid region.

Dynamics of seasonal stem radius variations

The long-term trend of the dendrometer curves indicated a pronounced seasonality of cambial activity, inferring that the whole season of stem radius increase corresponded with *phase 1*. The maximum daily amplitudes values located in the middle part of *phase 1* (May to August) corresponded with the highest air temperature and most abundant precipitation, possibly illustrating the main timing of stem radius increase. This conjecture is consistent with the research conclusions of Oladi et al. (2011) in Iran. In the late part of *phase 1*, with decreasing daily stem radius amplitudes, daily stem radius changes showed no obvious response to precipitation, indicating that the physiological activities were becoming more and more weak during this time. This suggested that only a little water was being consumed by transpiration. In *phase 1*, the daily amplitudes of stem radius variations became abnormally low when the mean air temperature fell below 0 °C on May 17 (– 2.06 °C) and on October 14 (– 0.17 °C) in 2010. This indicated that the air temperature level disturbed the physiological processes. Zweifel and Häsler (2000) found that frost shrinkage was not related to a particular timing during the day and occurs when the air temperature drops below – 5 °C. In our study, the lowest temperature (– 7.93 °C) suddenly occurred on May 18 in 2010, caused the synchronous shrinkage (as shown at the arrow in Fig. 8a), as the air temperature increased rapidly, the tree’s physiological activity again became normal. It could thus be inferred that during the growing season, the average air temperature had a more important physiological effect on stem radius growth, but steadily reducing minimum air temperature probably influenced tree’s growth.

In *phase 2,* the stem radius variations revealed a drastic decreasing trend during the period from October 24 in 2010 to February 2 in 2011. Zweifel and Häsler (2000) attributed this phenomenon to water transferred from bark to xylem. In this period the stem radius contraction was mainly caused by frost shrinkage, and swelling was mainly caused by thawing expansion. The fact that elastic living stem tissues sharply diminished in size during periods of temperatures below the freezing point had been reported in several studies (Winget and Kozlowski 1964; McCracken and Kozlowski 1965; Lemoine et al. 1999). Zweifel and Häsler (2000) used freezing experiments in the laboratory to elucidate the mechanism of stem radius decreasing in winter. They defined the diurnal stem radius variations as three processes: active radius change, frost shrinkage, and thawing expansion. They found that the process of active radius change depended on physiological activities and was not directly sensitive to the temperature course; the initial shrinkage always started in the morning and the expansion began in the afternoon and lasted through the night. The sudden radius decrease in winter were caused by water transport processes between bark and wood. This explained the radius increases in spring. In the process of frost shrinkage and thawing expansion, the stem radius changes were temperature-induced. The radius expanded during the day when the temperature increased and contracted during the night, which showed an inverse day and night time pattern of active radius change. This mechanism of stem radius change proposed by Zweifel and Häsler (2000) was well demonstrated in our research. In addition, the sample trees still exhibited weak physiological activities when the maximum air and soil temperature rose above 0 °C even though the mean air temperature remained below 0 °C (Fig.8b). This adaptation strategy of physiological activities to low temperature likely explained why the trees could live in so cold an environment. Individual tree specimens exhibited different capacities for sustaining physiological activity in winter, making the situation more complex. In *phase 2*, precipitation fell mainly as snow, which had almost no direct influence on stem radius change. However, the snowfall could influence water absorption when snow start to melt in spring, which could have an indirect effect on tree growth.

The drastic increment of stem radius variations in late part of *phase 2* (from February 3 to March 28 in 2011), were in agreement with several previous dendrometer studies (Zweifel and Häsler 2001; Deslauriers et al. 2003; Mäkinen et al. 2003). This increase in stem radius was most likely caused by increasing stem water content due to stem rehydration after winter desiccation. Generally, this period was called *spring rehydration* as the trunk size increases sharply (Tardif et al. 2001; Turcotte et al. 2009). The patterns of radius variations in this period were very complex because the processes of active radius change, frost shrinkage, and thawing expansion proposed by Zweifel and Häsler (2000) may have occurred on the same day. From our study data, the *spring rehydration* ceased when the mean air temperature rose above 0 °C, after which point the sub-daily patterns of stem radius change became very regular from the beginning of *phase 1*. Nonetheless, it was difficult to distinguish the exact beginning time of stem radius growth because we could not eliminate the possibility that stem growth simultaneously initiated with rehydration during *phase 2*. Therefore, other techniques such as micro-coring or pinning will have to be used to identify the precise onset of radial growth.

Conclusion

By analyzing the sub-daily stem radius shrinkage and expansion patterns of six specimens of Qilian juniper in arid northwestern China, we confirmed the three processes of stem radius variations that were proposed by Zweifel's and Häsler's (2000) laboratory freezing experiments, and the two phases of seasonal stem radius variations in boreal forests. According to the existing research results, *phase 1* likely represents the *stem growth* seasons, the early part of *phase 2* represents the stem *winter shrinkage* seasons, and late part of *phase 2* represents the stem *spring rehydration* seasons. The different durations of stem growth periods in 2010 and 2011 each, which corresponded with duration of above 0 °C mean air temperature, may reflected response of tree growth to global warming in this cold and arid mountains.

The continuous shrinkage and expansion patterns which lasting more than 24 h could be inferred from the beginning (0:00) and end (23:30) of each day. This sub-daily shrinkage and expansion patterns method provides deeper insight into the dynamics of tree-ring growth and the relationships between tree rings formation and climatic change. To gain deeper understanding of stem radius growth dynamics in response to climatic and environmental factors, more trees of dendrometer measurements and tracking of cambial activities should be considered for future study.

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Figure Captions and Tables

Table 1 Detailed information of the six sample trees. ***LL*** lower limit of the forest; ***ML*** middle location of the forest; ***CIR*** circumference; ***T*** the beginning time of dendrometer measurement in 2010 (LL1, LL2, LL3, ML1) and 2011 (LL4, ML2); ***D*** type of dendrometers

Fig. 1 Map showing the location of the research site (*triangle*) in the Qilian Mountains

Fig. 2 Two photographs of the study area. **a** The vegetation of the study area, dominated by Qinghai spruce on cloudy slopes and Qilian juniper on sunny slopes; **b** An automated weather station installed at the lower limit (LL) of the Qilian juniper pure forest. The two photographs were taken by Zhangyong Wang on 9 June, 2010

Fig. 3 Climate diagram for the Qilian station during 1957 – 2007

Fig. 4 Frequency distribution of daily stem radius extreme values (maximum and minimum) during the whole measurement periods: LL1 from March 7 in 2010 to November 20 in 2011; LL2 from June 20 in 2010 to November 20 in 2011; LL3 from August 26 in 2010 to November 20 in 2011; LL4 from January 24 to November 20 in 2011; ML1 from August 26 in 2010 to November 19 in 2011; ML2 from January 27 to November 19 in 2011. The *black bars* represent the daily maximum, *grey bars* represent the daily minimum, and *horizontal lines* represent the mean frequency distribution of every hour in ideal conditions

Fig. 5 Sub-daily shrinkage and expansion patterns of the six Qilian junipers. The *red dots* represent daily maximum values and the *blue triangles* represent daily minimum values. The *horizontal dash lines* at about 13:30 divide the days into two parts, morning and afternoon. *Phase 1* is from April 27 to October 23 in 2010 and from March 29 to November 3 in 2011, respectively; *phase 2* is from October 24 in 2010 to March 28 in 2011. The two phases are divided by *vertical lines*

Fig. 6 Daily maximum values of stem radius variations of the six sample trees (**a, b**) and climatic records of the LL weather station (**c, d, e**). Periods with interruptions of the individual curve are caused by data gaps due to failure of data registration by the data logger. **c** Daily maximum, minimum and mean air temperature (°C); **d** Daily relative humidity (%) and precipitation (mm); **e** Daily mean soil temperature (°C) and soil water content (100%) at 20 cm and 40 cm below ground, respectively. The two phases here (*vertical lines*) correspond with those presented in Figure 5; the two *black horizontal dash lines* represent the 0 °C level of air and soil temperature each

Fig. 7 Daily amplitudes of stem radius variations of the six sample trees. The two phases here (*vertical lines*) correspond with those presented in Figure 5.

Fig. 8 Stem radius variations and relation to air temperature and precipitation. *Black lines* represent stem radius variations; *red lines* represent air temperature; *light blue bars* represent precipitation. **a** From May 17 to 28 in 2010, stem radius variations were not directly sensitive to air temperature; the *arrow* shows that stem shrinkage respond to an air temperature drop to –7.93 °C on May 18, 2010; **b** From November 2 to 12 in 2010, the daily maximum air temperature were still above 0 °C, inferring the three processes proposed by Zweifel and Häsler (2000). The *grey bar* represents frost shrinkage (S); the *orange bar* represents thawing expansion (E); and the *green bar* represents active radius change (A); **c** From December 4 to 13 in 2010, the daily maximum air temperature dropped below 0 °C and the stem radius variations showed synchronous change with air temperature; **d** From February 1 to 16 in 2011, as the daily maximum air temperature increasing above 0 °C from February 3, the stem radius variations were increased rapidly around the same date; as the air temperature increased, three processes (frost shrinkage, thawing expansion, and active radius change) occasionally occurred on the same day, making the stem radius variations more complex; **e** From May 1 to 10 in 2011, stem radius variations depend on physiological activities and were not directly sensitive to the temperature course

Figure 1

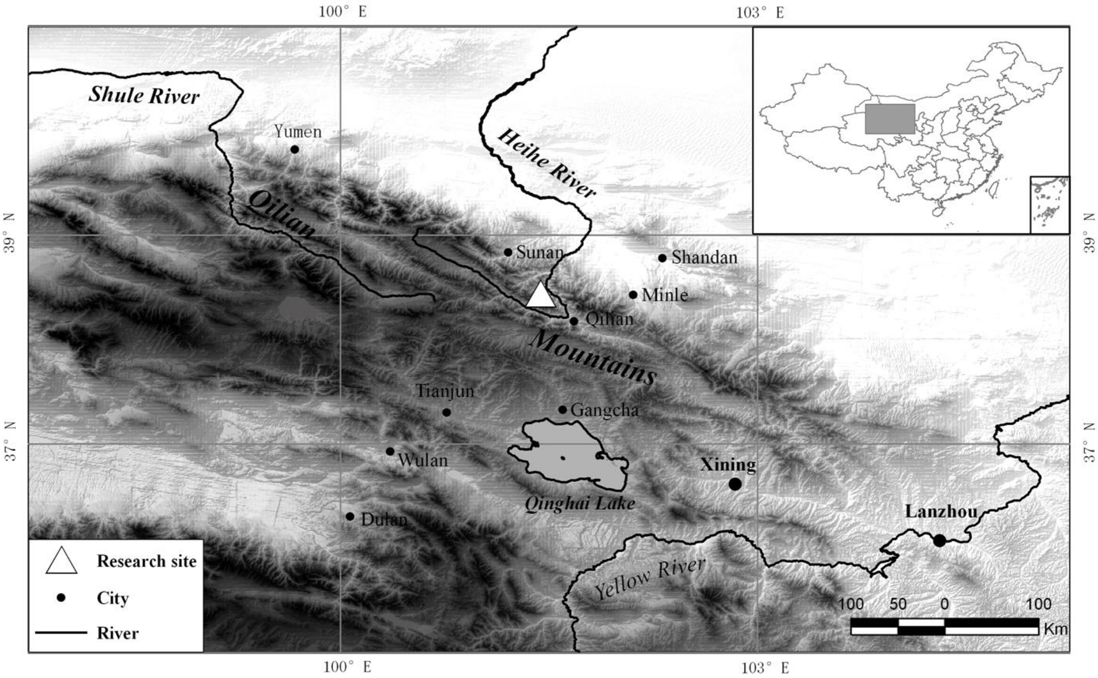

100° E
103° E
39° N
37° N
Shule River
Yumen
Heihe River
Qilian
Sunan
Shandan
Minle
Qilian
Mountains
Tianjun
Gangcha
Wulan
Xining
Qinghai Lake
Dulan
Lanzhou
Yellow River
Research site
City
River
100 50 0 100
Km

Figure 2

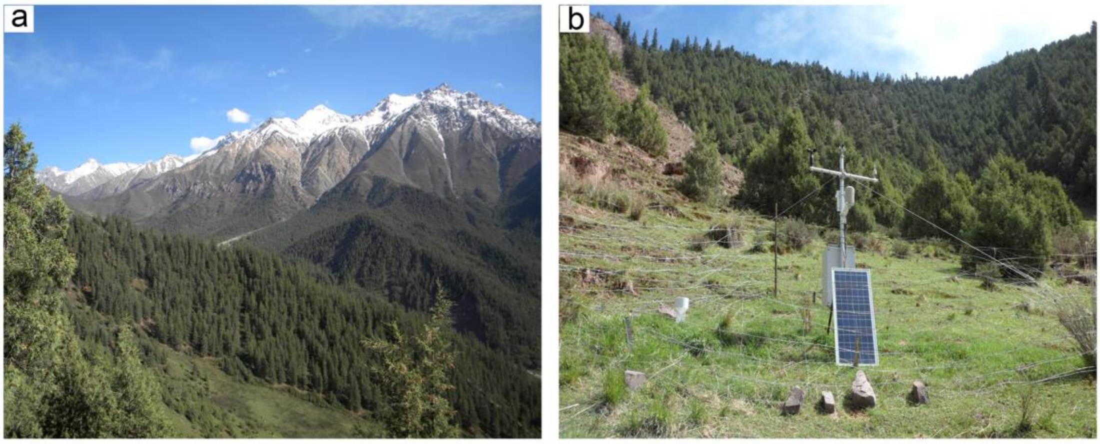
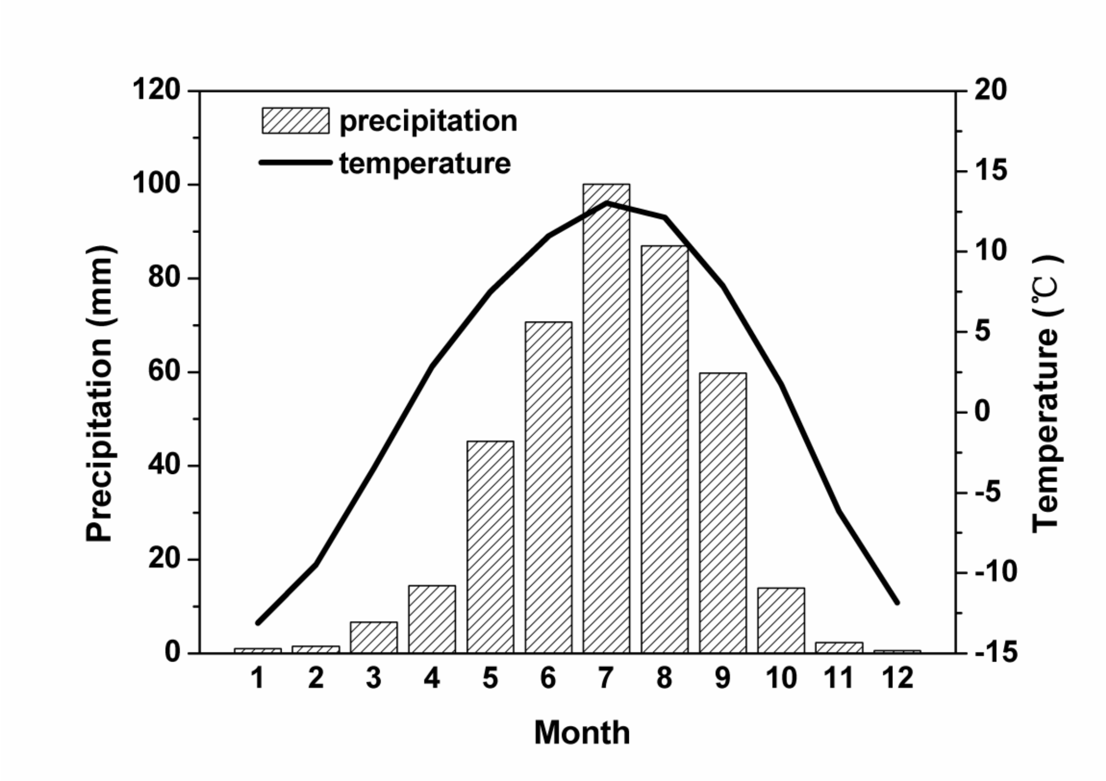


Figure 3



precipitation
temperature
Precipitation (mm)
Temperature (℃)
Month
120
100
80
60
40
20
0
20
15
10
5
0
-5
-10
-15
1
2
3
4
5
6
7
8
9
10
11
12

Figure 4

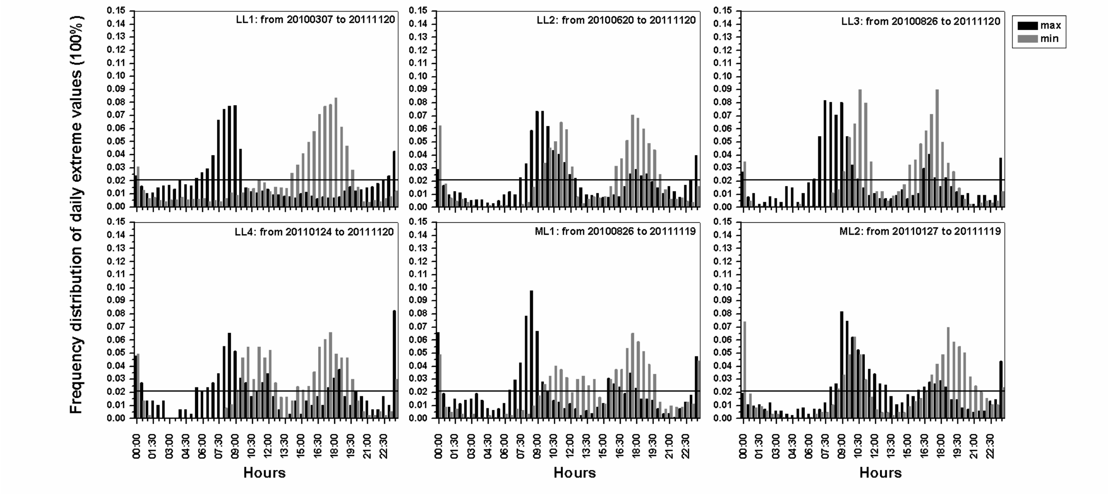

LL1: from 20100307 to 20111120
LL2: from 20100620 to 20111120
LL3: from 20100826 to 20111120
max
min
LL4: from 20110124 to 20111120
ML1: from 20100826 to 20111119
ML2: from 20110127 to 20111119
Frequency distribution of daily extreme values (100%)
Hours

Figure 5

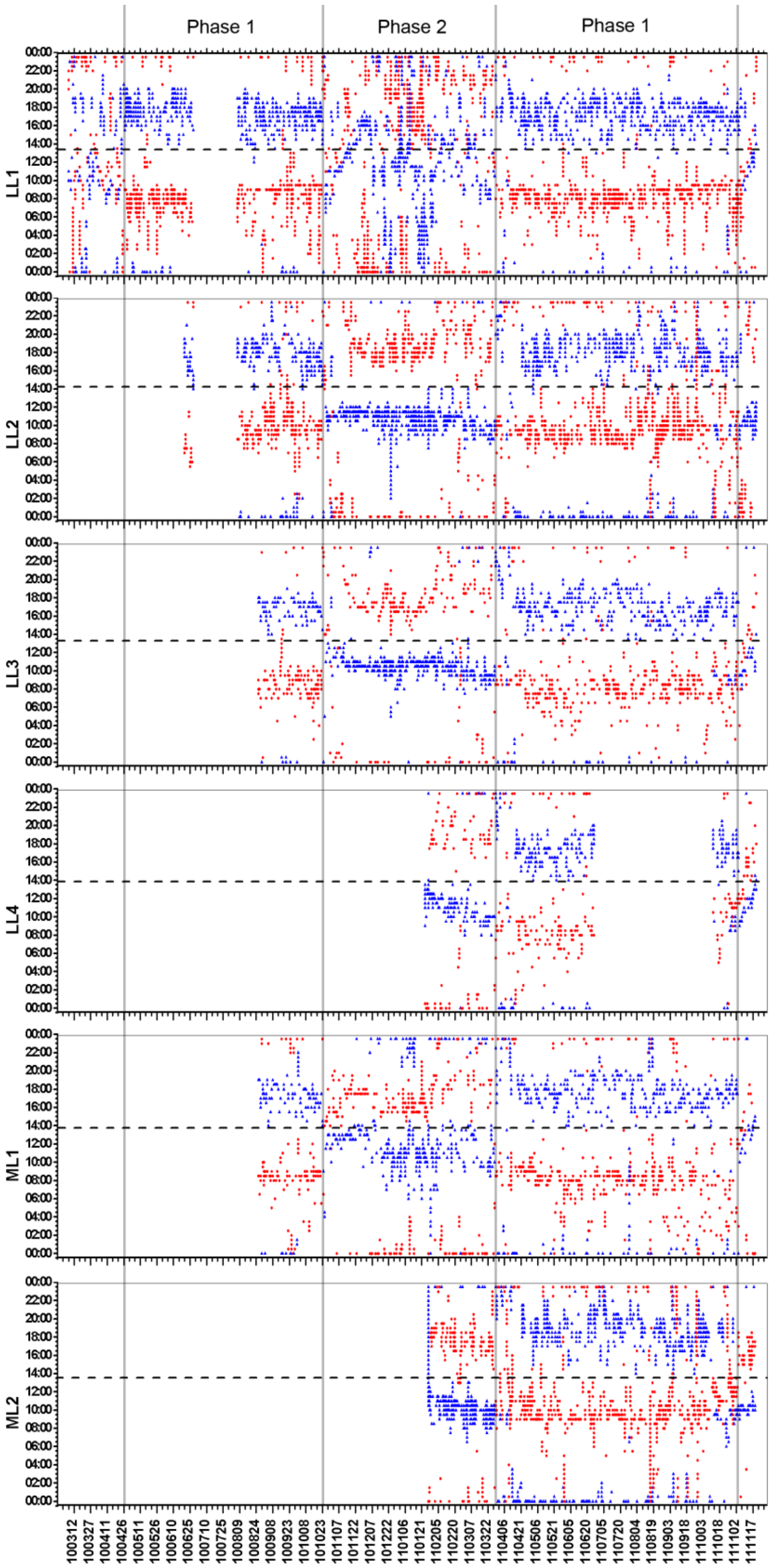
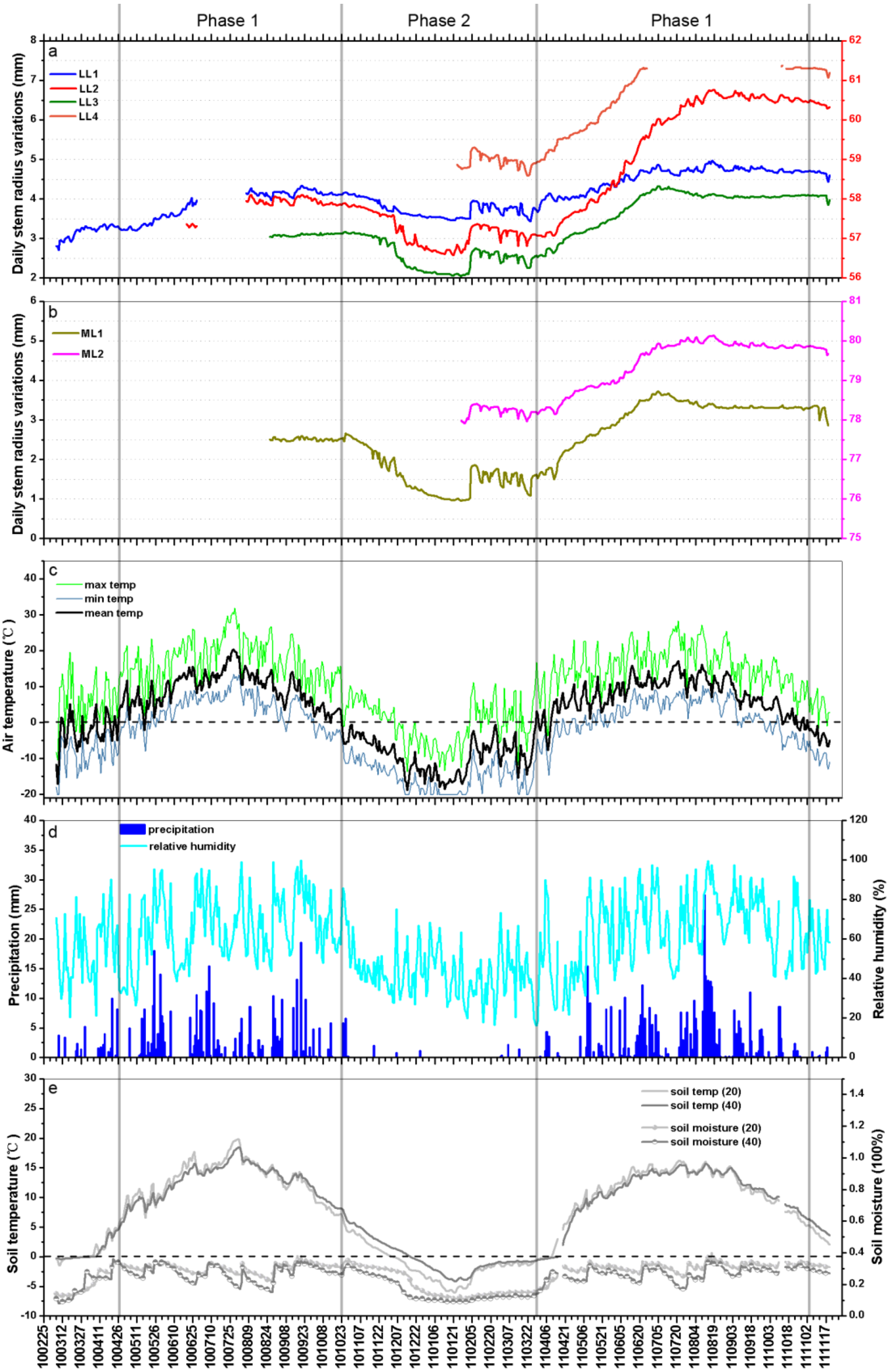
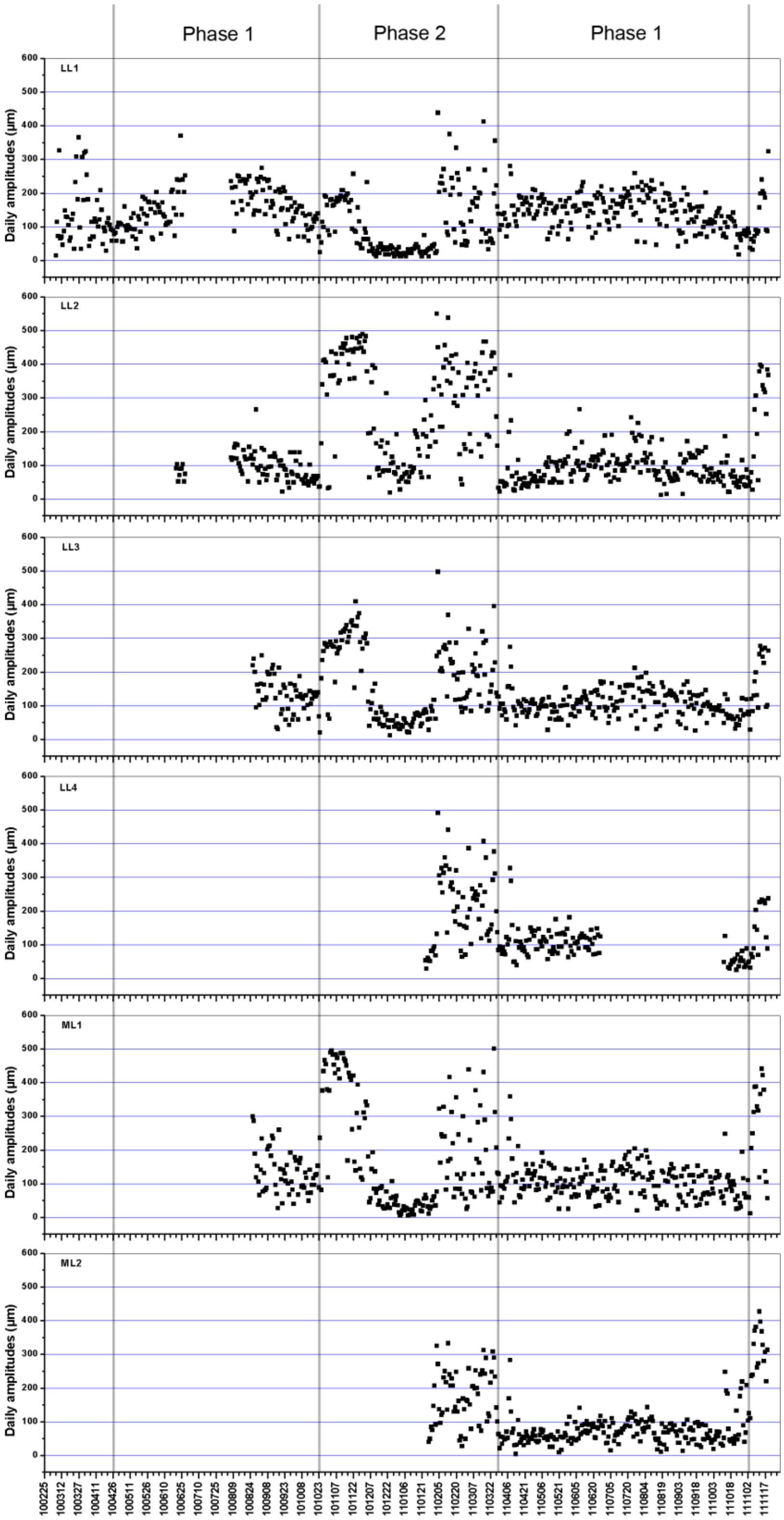

Phase 1
Phase 2
Phase 1
LL1
LL2
LL3
LL4
ML1
ML2
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
100312
100327
100411
100426
100511
100526
100610
100625
100710
100725
100809
100824
100908
100923
101008
101023
101107
101122
101207
101222
110106
110121
110205
110220
110307
110322
110406
110421
110506
110521
110605
110620
110705
110720
110804
110819
110903
110918
111003
111018
111102
111117

Figure 6



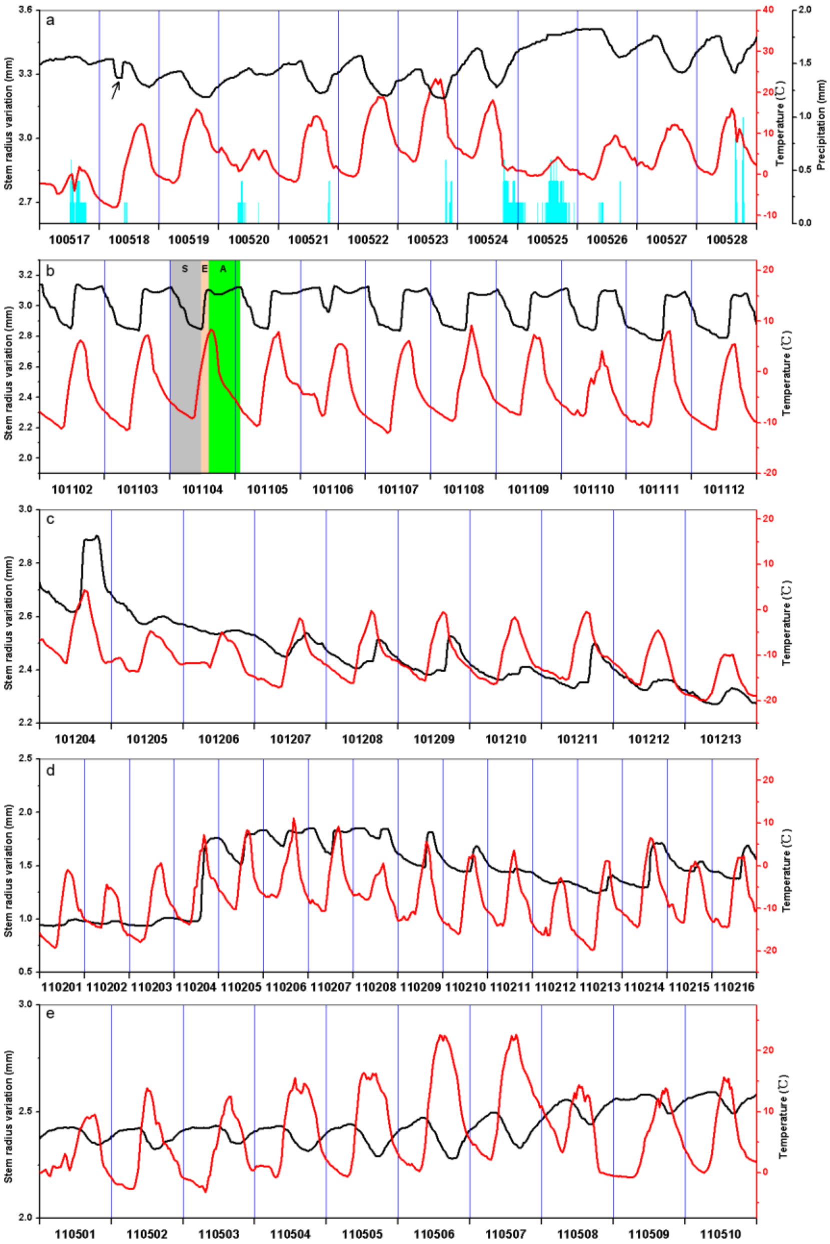
Phase 1
Phase 2
Phase 1
a
LL1
LL2
LL3
LL4
Daily stem radius variations (mm)
b
ML1
ML2
Daily stem radius variations (mm)
c
max temp
min temp
mean temp
Air temperature (℃)
d
precipitation
relative humidity
Precipitation (mm)
Relative humidity (%)
e
soil temp (20)
soil temp (40)
soil moisture (20)
soil moisture (40)
Soil temperature (℃)
Soil moisture (100%)

Figure 7



Phase 1
Phase 2
Phase 1
LL1
LL2
LL3
LL4
ML1
ML2
Daily amplitudes (µm)
0
100
200
300
400
500
600
100225
100312
100327
100411
100426
100511
100526
100610
100625
100710
100725
100809
100824
100908
100923
101008
101023
101107
101122
101207
101222
110106
110121
110205
110220
110307
110322
110406
110421
110506
110521
110605
110620
110705
110720
110804
110819
110903
110918
111003
111018
111102
111117

Figure 8


a
b
c
d
e
S
E
A
Stem radius variation (mm)
Temperature (℃)
Precipitation (mm)
100517
100518
100519
100520
100521
100522
100523
100524
100525
100526
100527
100528
101102
101103
101104
101105
101106
101107
101108
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101110
101111
101112
101204
101205
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101211
101212
101213
110201 110202 110203 110204 110205 110206 110207 110208 110209 110210 110211 110212 110213 110214 110215 110216
110501
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110510