Original article

Climatic responses of tree-ring widths of *Larix gmelinii* on contrasting north- and south-facing slopes in central Siberia

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Key words

Larix gmelinii, Siberia, permafrost, climatic response, tree-ring width

Footnote

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Abstract

An analysis was performed of the climatic responses of the radial growth of *Larix gmelinii* (Rupr.) Rupr. on contrasting north- and south-facing slopes in Tura, central Siberia. We developed chronologies of tree-ring width for four plots, designated north-upper, north-lower, south-upper and south-lower. Both residual and standard chronologies of tree-ring widths exhibited a significant positive correlation with temperature from the end of May until the early June in all four plots. The chronologies of ring width did not reveal any major differences in the response to temperature among the four plots. The standard chronologies of ring widths on the north-facing slope were negatively correlated with precipitation during the winter (October-April) and in early and mid May, whereas the residual chronologies did not reveal clear relationships with precipitation during the winter and May. The significant correlation between ring width and temperature from the end of May until the early June indicate that temperatures in springtime play a significant role in the radial growth of *L. gmelinii*. The negative correlations between standard chronologies of tree-ring width and precipitation in the winter and in May on the north-facing slope indicate that low-frequency fluctuations in snow fall have negative effects on the radial growth, however the effect vary and depend on micro-scale topography.

Introduction

The Siberian boreal forest, which is the largest terrestrial carbon pool in the northern hemisphere, has the greatest potential to affect the global storage of carbon[1]. For the most part, Siberian boreal forests are dominated by deciduous *Larix* species, which possess about 35 % of the total carbon storage of the forests of Russia[2,3]. Thus, the responses of radial growth of larch trees to climatic change can significantly influence the carbon pool of the Eurasian boreal forest.

At the northern timberline in the continuous-permafrost region in the Siberian subarctic, the ring widths of coniferous species are positively influenced by temperatures in June-July[4]. Similar results have been obtained for *Larix* species (*L. sibirica, L. gmelinii* and *L. cajanderi*) in the same region[5,6]. In addition, Kirdyanov et al.[6] postulated that the date of snowmelt is a significant factor in the control of the initiation of radial growth of larch trees. At present, published information on the responses of Siberian larch trees to climate remains limited and little research has been done on mechanisms responsible for the responses of tree-ring parameters to climate variables under varying growth conditions.

Topographical features of the landscape, such as slope exposure, create microclimatic differences. Kirchhefer[7] reported differences in the responses of tree-ring widths of *Pinus sylvestris* to temperature and precipitation between the north- and south-facing slopes in north of the Arctic Circle in Norway. Koike et al.[8] reported differences in shoot morphology, rates of photosynthesis and nutrient conditions of *L. gmelinii* in active soil layers of different depths on contrasting north- and south-facing slopes in central Siberia. Because of changes in the active layer that might be expected to occur as a result of possible future changes in climate, it is important to identify the responses of the radial growth of larch trees to climate variables under different micro-site conditions with varying active layers of permafrost.

The purpose of the present study is to clarify the influence of temperature and precipitation on tree-ring widths of *Larix gmelinii* (Rupr.) Rupr. growing on contrasting north- and south-facing slopes in central Siberia. A comparison of the growth responses of tree-ring widths to climate variables between the two slopes should help to clarify the impact of temperature and precipitation on the radial growth of larch trees growing under specific conditions with micro-scale variations and to identify mechanisms that control radial growth.

Materials and methods

Study site and sample trees

The study site is located in the Tura Experiment Forest (64°19’N, 100°13’E; 200 m a.s.l.) of the Sukachev Institute of Forest (Siberian Branch, Russian Academy of Science, Russia), on the Central Siberian Plateau, close to the western edge of a region of continuous permafrost (Fig. 1).

The climate of the region is continental, with very cold winters and relatively warm summers. The mean annual temperature is –7.6 °C, as determined at the Tura Meteorological Station (Russian Research Institute of Hydrometeorological Information – World Data Center, RIHMI-WDC; http://www.meteo.ru/data/emdata.htm). The mean temperature in January is –36.5 °C and that in July is 17.3 °C. The mean annual precipitation is 380 mm.

We chose contrasting north- and south-facing slopes that are divided by a small stream (Fig. 2). The study site is located about 10 km north-west from Tura Meteorological Station. The difference of elevation between riverbed and hilltop is approximately 30 m, and the gradient of the slope is 18° on the south-facing slope and varies between 8° and 18° on the north-facing slope. The south-facing slope is almost entirely occupied by *L. gmelinii*, whereas the north-facing slope is dominated by *L. gmelinii* with a small proportion of *Picea obovata*[8]. The forest stand became established after a forest fire that occurred in the early 1800's. Forest stand on the north-facing slope is uneven-aged, caused by survivors of the forest fire, whereas the south-facing slope seems to be even-aged. The depth of the active soil layer differs markedly between the two slopes, being 148±5 cm on the south-facing slope and only 45±8 cm on the north-facing slope in the summer of 1997[8]. We divided the study site into four plots (approximately 40 x 20 m each) by dividing the south- and north-facing slopes into upper and lower part (abbreviate as NU, NL, SU and SL), because we assumed that differences in soil moisture between the upper and lower parts of the slopes might cause. We chose to examine 30 dominant specimens of *L. gmelinii* per plot.

Development of chronologies

We extracted two increment cores of 5 mm in diameter from each sample tree at breast-height parallel to contour of the slope. This procedure provided 60 cores per plot, giving a total of 240 cores, which were smoothed with fine sandpaper and a razor blade. The tree-ring widths were measured at 0.01 mm precision under a stereomicroscope (MZ6; Leica, Solms, Germany) with a system for tree-ring measurement from Velmex Inc. (Bloomfield, NY, USA). The series of tree-ring widths were cross-dated visually by using skeleton plot procedures and confirmed by a statistical method to ensure that the correct date was assigned to each annual ring[9]. Statistical cross-dating was performed with the COFECHA program[10]. Some core samples in which there was evidence of the extensive formation of reaction wood were excluded because of cross-dating difficulties. The series of tree-ring measurements were standardized by fitting smoothing splines with a 50% frequency-response cutoff of 80 years to eliminate growth trend such as an age-related decline in growth rate and low-frequency variance due to natural disturbance[11]. A standardized series usually exhibits autocorrelation that negates the assumption of the independence that is necessary for most statistical analyses[12, 13]. In order to remove the effects of autocorrelation, we transformed each of standardized series to a residual series through pooled autoregressive (AR) modeling[14]. Standardization and autoregressive modeling were performed with the ARSTAN program[14]. Standard and residual chronologies for the plots were developed by averaging the individual series by using a biweight robust mean. Expressed population signal (EPS) analysis[15,16] was used to assess the degree to which chronologies of each plot portraits the hypothetical perfect chronology.

Responses to climate variables

We analyzed the responses of ring widths to climate variables by calculating the simple correlations between both the residual and standard chronologies and climate variables. We used standard chronologies to analyze the effect of low-frequency fluctuations in climate because residual chronologies lost low-frequency fluctuation through AR modeling.

The climatic data used for calculations were obtained from the Tura Meteorological Station. Monthly mean temperatures and average daily mean temperatures for five consecutive days (pentads)[4] from May of the previous year to August of the current year were used in the analysis. We did not use the data after August of the current year because the radial cell division finished until August (unpublished). We chose to use pentads analysis because previous studies for coniferous species in Siberia reported strong relationships exist between tree-ring width and temperature in shorter time-spans (5 days)[4-6]. We used monthly precipitation from previous May to current August. The precipitation during winter was calculated as the cumulative precipitation from November of the previous year to April of the current year because it falls as snow. In addition, the precipitation in May of the current growing season was divided into precipitation for the early, middle and late part of the month for assessment of the short-term influence of precipitation of late winter and early spring. The analyses of ring widths and temperature covered the period from 1930 to 1995 (n=65). The analyses of ring widths and precipitation covered the period from 1939 to 1995 (n=56).

Observations on snowmelt and leaf development

For observations of the timing of the snowmelt on the contrasting slopes in the spring of 2004, we installed an automatic camera (KADEC21-EYE; Kona Systems, Sapporo, Japan) at the study site in the autumn of 2003. The snow cover on the ground on both slopes was visible in each photograph. One image per day was taken at noon.

Leaf initiation and expansion stages were observed visually in the spring of 2004, from 29 May to 14 June. Visual observations were made at four different observation sites located within 30 km of the study site during the fieldwork period.

Results and Discussion

Snowmelt and leaf development

Snowmelt in the spring of 2004 occurred on 19 May on the south-facing slope and on 25 May on the north-facing slope. No major differences in stages of leaf development were found among the four observation sites. Leaf initiation at Tura town, 10 km from the study site, occurred at 25 May and leaf expansion continued until the middle of June. At the study site, no major differences were observed in the stages of leaf development between the two slopes observed at 9 June.

Chronology statistics

Cross-dating was successfully performed for all four plots. One core sample from SL and fourteen core samples from NU were excluded from the analysis because of extensive formation of reaction wood. Absent rings were identified through cross-dating procedure (Table 1). They usually occurs in the years that other cores exhibit very narrow rings. Both residual and standard chronologies of ring width were successfully constructed for all the plots from early 1800's and satisfied the minimum EPS threshold of 0.85[16] (Table 1, Fig. 3).

The basic statistics of the chronologies are shown in Table 1. The standard chronologies on the north-facing slope markedly yielded lower mean sensitivities, which is the average relative difference from one ring width to the next. They also revealed higher first-order autocorrelations and lower correlations between trees compared with those for the south-facing slope. The residual chronologies on the north-facing slope also yielded lower mean sensitivities and correlations between trees.

Responses to temperature

June monthly mean temperature of the current year exhibited significant correlations with residual chronologies of ring widths in all the plots (Fig. 4). July temperatures of the previous growing seasons exhibited negative correlation with ring widths in SU. At the analysis on shorter time-spans, the residual chronologies of tree-ring width were significantly and positively correlated with temperature from the end of May until the early June in all four plots (Fig. 5). Temperatures in late June and end of July to beginning of August of the current growing season also exhibited significant positive correlations with ring widths in all the plots. The temperature from May 10 to May 14 of the previous growing season was correlated with ring width in all four plots. The temperatures of early December, early March and early April that preceded growth exhibited negative correlations with tree-ring widths in some of the plots.

The standard chronologies also revealed significant and positive correlations with temperature from the end of May until the early June in all four plots (Fig. 6). The temperature of mid May of the previous growing season revealed the highest correlation in all four plots.

Both analyses on residual and standard chronologies indicated that temperatures from end of May to early June played the most significant role in the radial growth of *L. gmelinii*. There were no major differences in the responses of ring widths on the north- and south-facing slopes to temperature. In addition, no major differences in the responses of ring widths were present on the upper- and lower parts of the both slopes. On both slopes, the period of significant correlation also coincided with the observed leaf flushing (25 May) and subsequent stages of leaf development until the early June in the spring of 2004. This observation indicates that differences in site-specific conditions (e.g., the depth of the active layer of permafrost) do not influence the responses of tree-ring widths to temperature. The spring temperatures might directly affect stages of leaf development and the related radial growth of stems. Our present results confirm the results of earlier studies in Siberia revealing the temperature in June is one of the most important factors that define radial growth[4, 6].

Responses to precipitation

The residual chronology of tree ring width in NU was negatively correlated with precipitation during the early May prior to growth (Fig. 7). Ring width in SL was positively correlated with precipitation in August of the previous growing season. On the other hand, the standard chronology of tree ring width in NU was negatively correlated with precipitation during the winter and from early to mid May prior to growth (Fig. 8). Ring widths in NL were also negatively correlated with precipitation in early May of the current year. Both standard chronologies on the north-facing slope were negatively correlated with precipitation in May of the previous year. By contrast, standard chronologies of tree-ring widths in SU and SL were not significantly correlated with precipitation of winter and May of the current year. That in SL was positively correlated with precipitation in August of the previous year.

In the south-facing slope, both residual and standard chronologies did not reveale significant correlations with precipitation of winter or May. By contrast, in the north-facing slope, differences in responses to precipitation of winter and May existed between residual and standard chronologies. The weak correlations with residual chronologies indicate that the precipitation of winter and May do not affect year-to-year (high-frequency) variations in ring widths. On the other hand, the negative correlations between standard chronologies and precipitation of winter and May indicate a possibility that low-frequency fluctuations in precipitation influence the radial growth.

The low-frequency variations in standard chronologies revealed opposite trend with that in precipitation of winter and May (Fig. 9). The decreasing trend from late 1960s to early 1970s in standard chronologies in the north-facing slope coincided with increasing trend in both winter and May precipitation. The increasing trend from mid 1970s to mid 1980s in standard chronologies coincided with decreasing trend in winter and May precipitation. The above mentioned trends were not clearly seen in residual chronologies at the north-facing slope and in both standard and residual chronologies at the south-facing slope (Figs. 3 and 9). These results suggest that precipitation of winter and May influence the low-frequency variations in ring width of larch trees growing in the north-facing slope.

The changes in precipitation of winter and early to middle May might consequent to changes in snow accumulation in spring, because average temperature of early May remains below freezing. Delayed soil thawing caused by accumulated snow in spring might lead to decrease in depth of active soil layer and to limit duration of root activity. The role of roots of larch trees growing in nutrient-poor permafrost soils thought to be important showing high allocation rate of biomass to roots [17]. It can be hypothesized that cumulative inhibition on root activity by snowfall that shows low-frequency fluctuations may results in decline in radial growth of larch trees in north-facing slope where active soil layer is shallow.

The lower mean sensitivities in north-facing slope (Table 1) may be due to the predominant effect of precipitation with low-frequency fluctuation compared with south-facing slope. The higher first-order autocorrelations in north-facing slope (Table 1) can also be attributed to predominance of low-frequency fluctuation. It can also be associated to slow rate of carbon turnover. Kagawa et al.[18, 19] reported that assimilated carbon was carried-over and used to xylem development of following years and the carbon turnover rate of *L. gmelinii* in Siberian permafrost was slower than that of temperate trees. There is possibility that higher first-order autocorrelation is due to higher rate of carry-over of photo assimilate to following years in the north facing slope.

Vaganov et al.[4] and Kirdyanov et al.[6] proposed that the date of snowmelt, that were estimated from temperature and winter precipitation, has a significant effect on ring width. They stated that the trend towards increasing precipitation in winter and a delay in snowmelt might have a significant effect on the radial growth of larch trees in Siberia. The present study revealed similar results for the north-facing slope; however, no significant response to snow cover was identified on the south-facing slope. Thus, the negative effect of snow cover seems to vary and to depend on micro-scale topography. The present study suggests that changes in spring temperatures and accumulate snow are important while assess the effect of future changes in climate on radial growth of *L. gmelinii* in central Siberia. The study also suggests the importance of micro-scale topography while assessing the effects of snow accumulation.

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Table 1. Plots and chronology statistics for the study site

Plot	**NU**	**NL**	**SU**	**SL**
DBH with standard deviation (cm)	16.8±3.7	18.3±4.0	20.1±2.2	20.3±1.9
DBH minimum-maximum (cm)	12.5-31.5	10.5-32	16-25	13-24.5
Starting year of chronology	1606	1590	1812	1818
Number of trees (radii) in chronology	28 (46)	30 (60)	30 (60)	30 (59)
Ring-width mean (mm)	0.32	0.33	0.43	0.42
Percentage of absent rings (%)	0.83	0.45	0.47	0.44
Standard chronology				
Mean sensitivity	0.18	0.18	0.24	0.24
Standard deviation	0.25	0.25	0.25	0.24
First-order autocorrelation	0.63	0.64	0.34	0.34
VARAR1 % [a)]	41.4	43.1	11.4	11.7
Correlation between trees [b)]	0.28	0.30	0.41	0.47
Expressed population signal (EPS)	0.93	0.93	0.93	0.94
Minimum sample size for ESP 85%	13	13	13	12
Subsample signal strength > 0.85 (SSS) [c)]	1800	1812	1821	1821
Residual chronology				
AR model order	3	2	1	1
Mean sensitivity	0.20	0.18	0.26	0.26
Standard deviation	0.18	0.16	0.23	0.22
First-order autocorrelation	0.03	0.01	0.05	0.07
Correlation between trees [b)]	0.33	0.34	0.51	0.52
Expressed population signal (EPS)	0.93	0.94	0.94	0.94
Minimum sample size for ESP 85%	12	12	12	12
Subsample signal strength > 0.85 (SSS) [c)]	1800	1812	1820	1821

[a)] VAR_{AR1} %: variance due to first-order autocorrelation.

[b)] Calculated for the common interval from 1862 to 2002.

[c)] Earliest year for which SSS of the chronology is greater the 85% of the original EPS.

Figure legends

Fig. 1. Geographical location of the study site (■). The map shows the distribution of the permafrost in the Northern Hemisphere and the range of distribution of *Larix* species in Eurasia. Redrawn from Environmental Defense Fund[20] and Abaimov et al.[3]

Fig. 2. Schematic representation of the study site. The depths of the active layers on the two slopes, as indicated by the dotted line, are taken from Koike et al.[8] Horizontal dotted lines indicate the border of the upper and lower plots.

Fig. 3. Chronologies of tree-ring widths for *Larix gmelinii* on the north-facing (NU and NL) and south-facing (SU and SL) slopes of the site in Tura, central Siberia. Solid lines indicate residual chronologies and dotted lines indicate standard chronologies. The number of cores (solid) and trees (dotted) included per plot are indicated by the bottom lines.

Fig. 4. Correlations between residual chronologies of tree-ring width and monthly temperature for *Larix gmelinii* on the north- and south-facing slopes of the site in Tura, central Siberia. The meteorological data used were from May of the previous year to August of the current year. Solid horizontal lines indicate the level at which the correlation is significant (p = 0.05). Black bars indicate significant correlations (p < 0.05). Sinusoidal curves show mean values of monthly average temperatures calculated for the period from 1930 to 1995.

Fig. 5. Correlations between residual chronologies of tree-ring width and five-day average temperature for *Larix gmelinii* on the north- and south-facing slopes of the site in Tura, central Siberia. Sinusoidal curves show mean values of five-day average temperatures calculated for the period from 1930 to 1995. For further details see Fig. 4.

Fig. 6. Correlations between standard chronologies of tree-ring width and five-day average temperature for *Larix gmelinii* on the north- and south-facing slopes of the site in Tura, central Siberia. For further details see Fig. 5.

Fig. 7. Correlations between residual chronologies of tree-ring width and precipitation for *Larix gmelinii* on the north- and south-facing slopes at the site in Tura, central Siberia. W, Winter (November to April) accumulation; ME, early May; MM, middle May; ML, late May; letters of the alphabet indicate months. For further details see Fig. 4.

Fig. 8. Correlations between standard chronologies of tree-ring width and precipitation for *Larix gmelinii* on the north- and south-facing slopes at the site in Tura, central Siberia. For further details see Fig. 7.

Fig. 9. Variations in precipitation of winter (November to April) and May observed at Tura Meteorological Station, and standard chronologies of tree-ring width for four plot in Tura, central Siberia. Dotted lines indicate standard chronologies and solid lines indicate trend curves calculated by 5 year moving average.

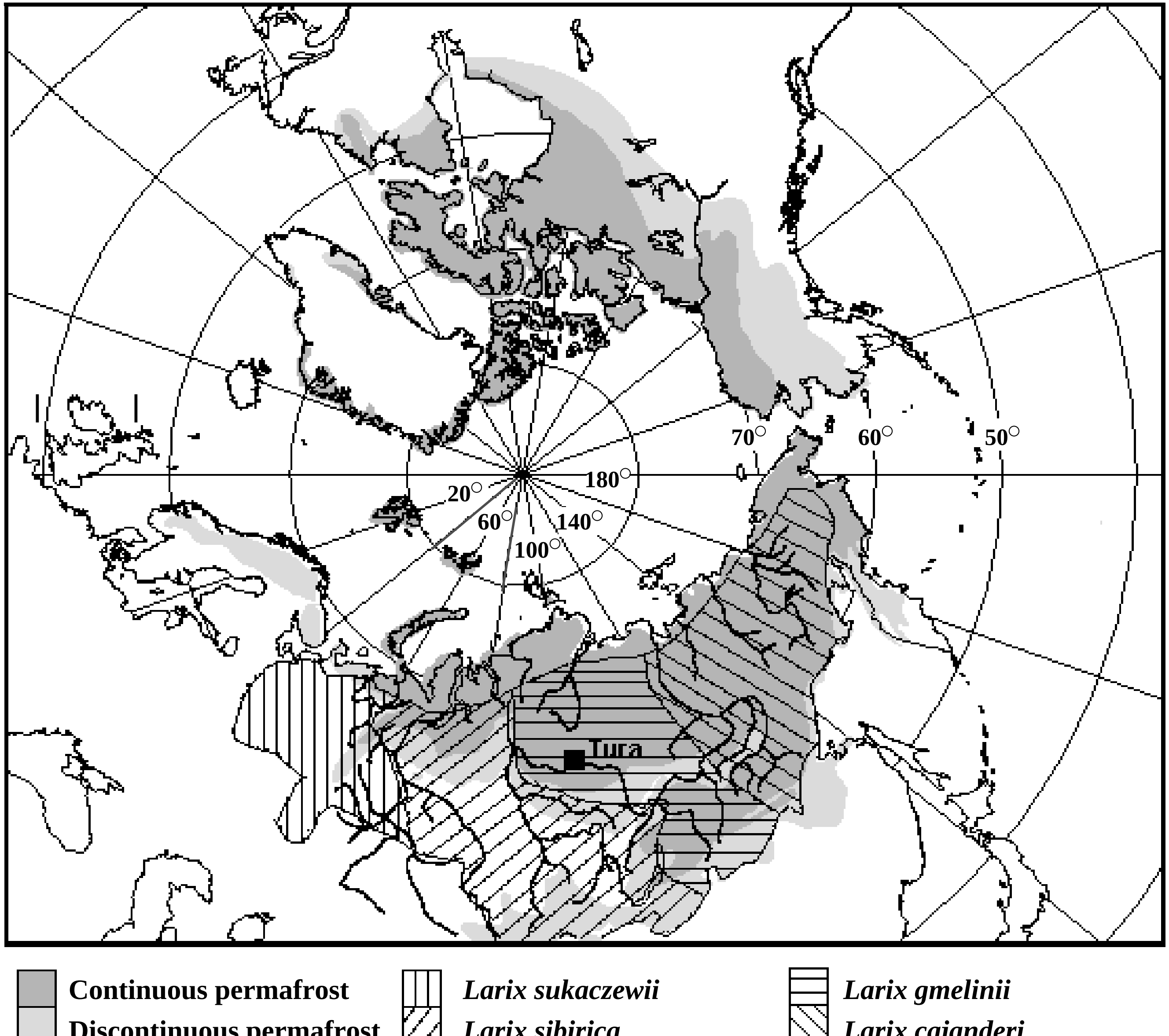

70°
60°
50°
180°
20°
60°
140°
100°
Tura
Continuous permafrost
Discontinuous permafrost
Larix sukaczewii
Larix sibirica
Larix gmelinii
Larix cajanderi

Fig. 2

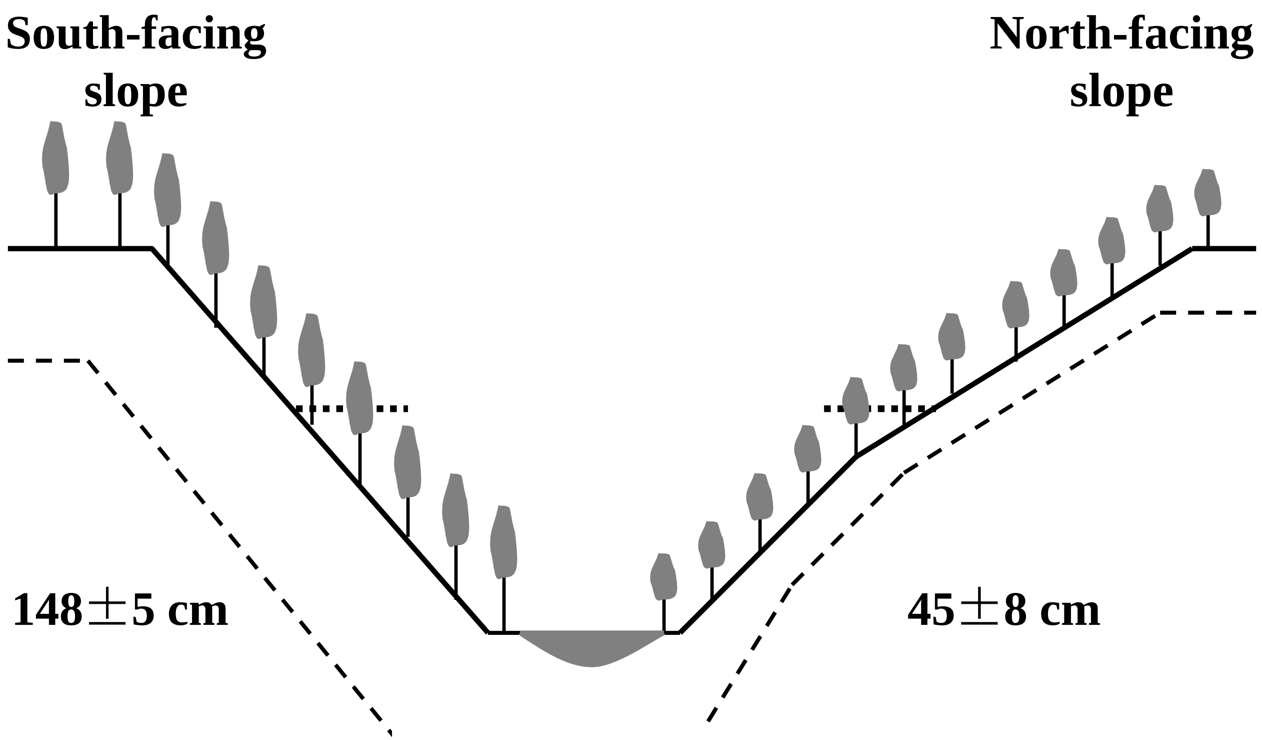
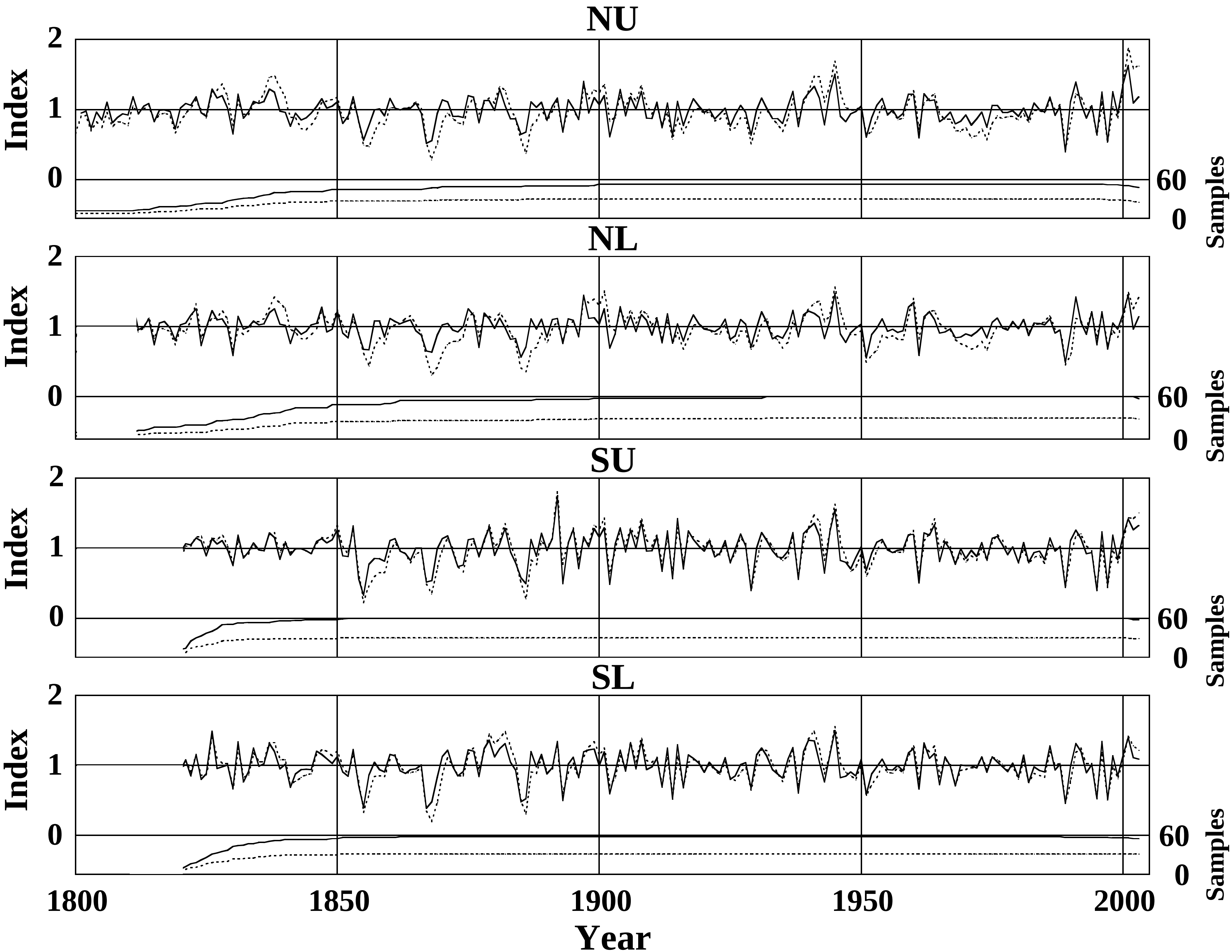
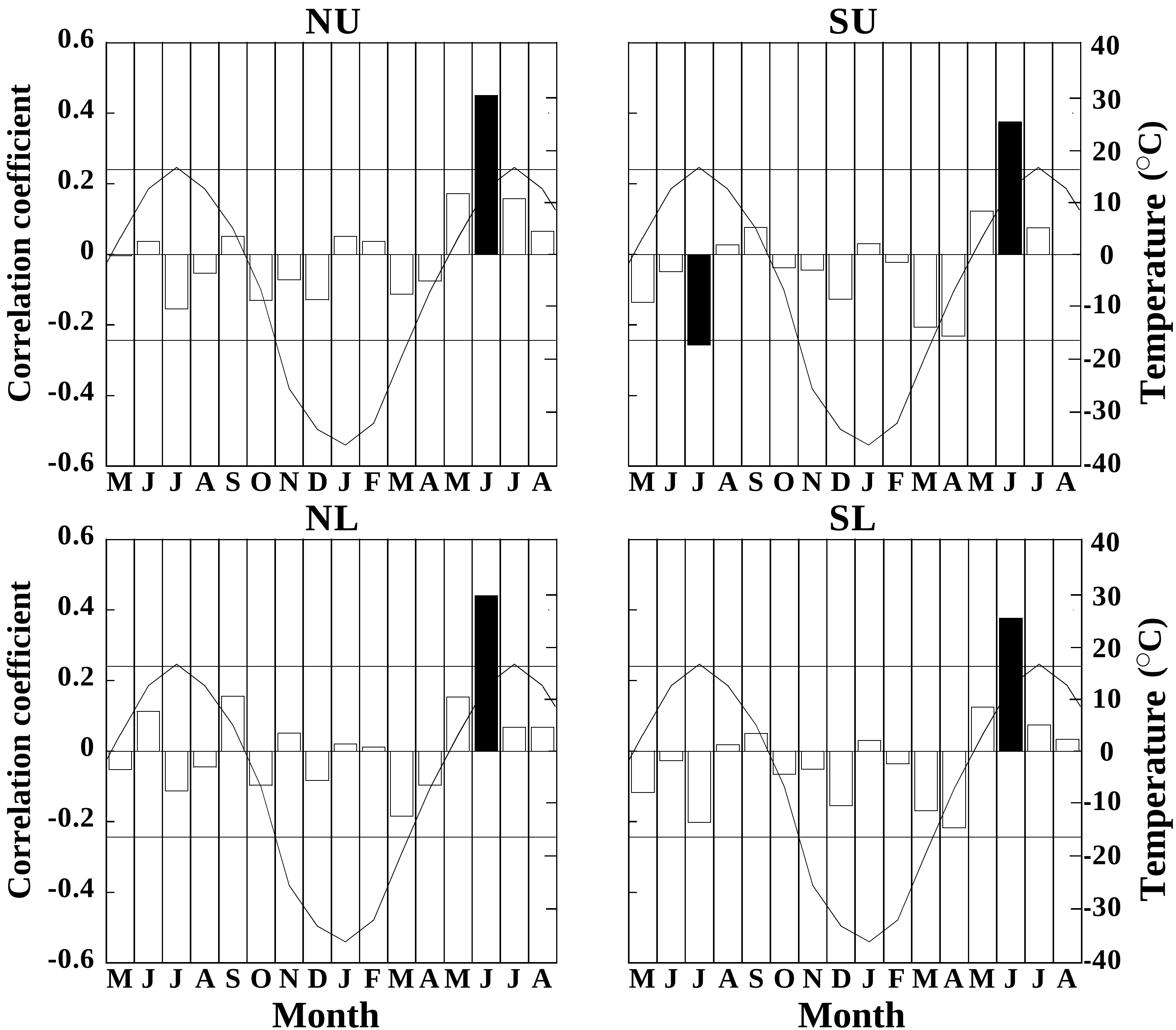


Fig. 3



NU
NL
SU
SL
Index
2
1
0
60
0
Samples
1800
1850
1900
1950
2000
Year

Fig. 4


NU
SU
NL
SL
Correlation coefficient
Temperature (°C)
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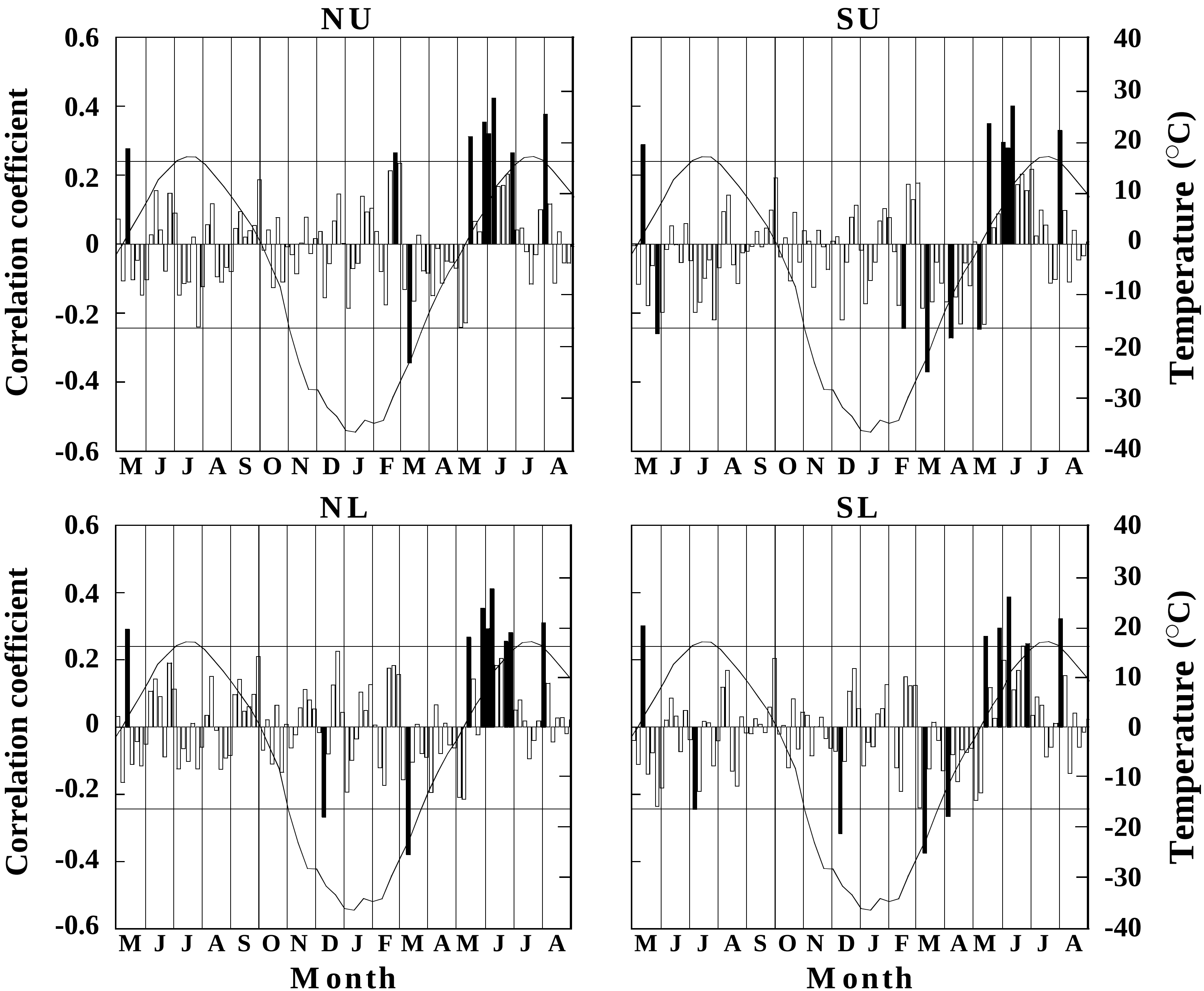
0.4
0.2
0
-0.2
-0.4
-0.6
40
30
20
10
0
-10
-20
-30
-40
M J J A S O N D J F M A M J J A
Month


NU
SU
NL
SL
Correlation coefficient
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Temperature (°C)
40
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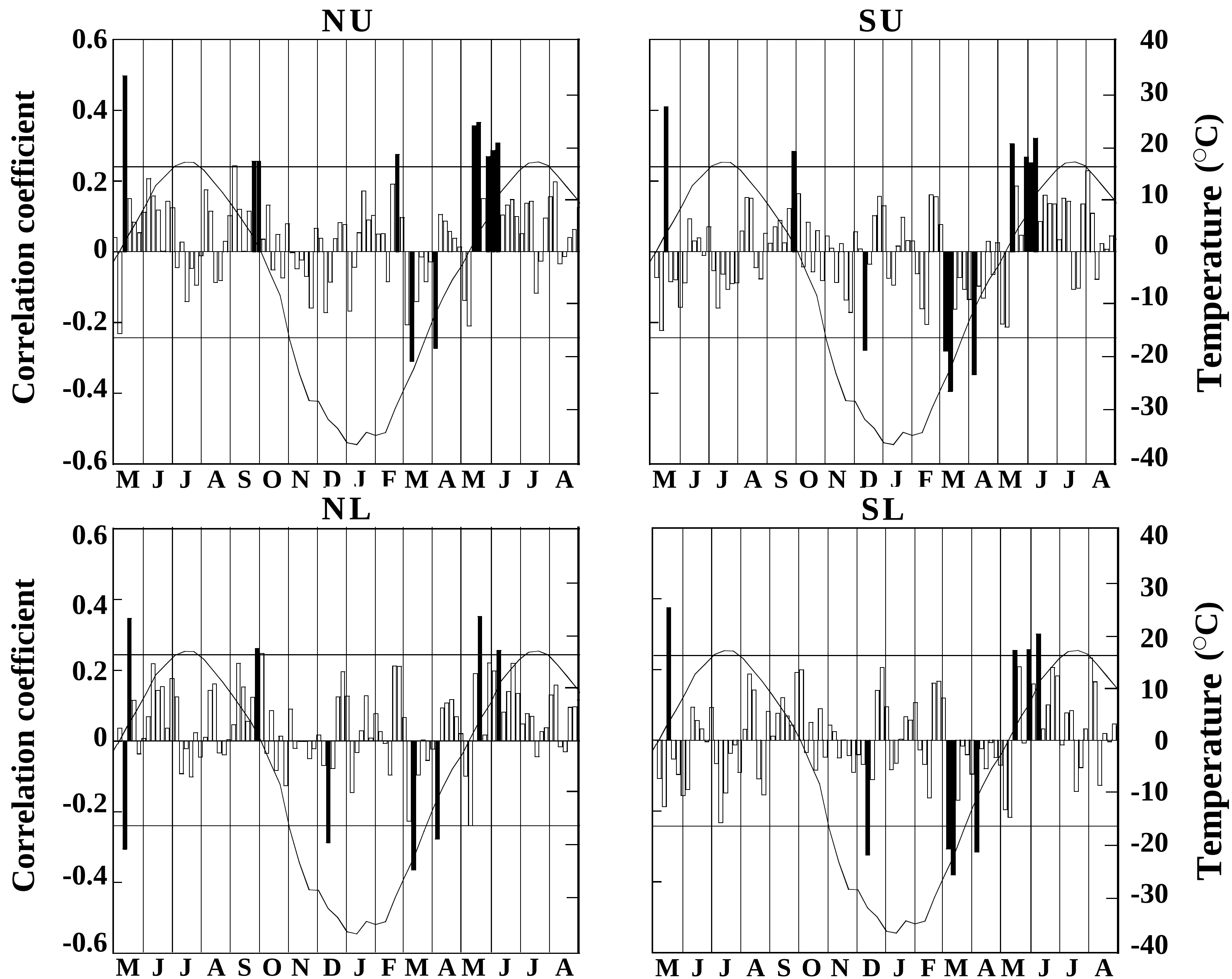
20
10
0
-10
-20
-30
-40
M J J A S O N D J F M A M J J A
Month

Fig. 6


NU
SU
NL
SL
Correlation coefficient
Temperature (°C)
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0.4
0.2
0
-0.2
-0.4
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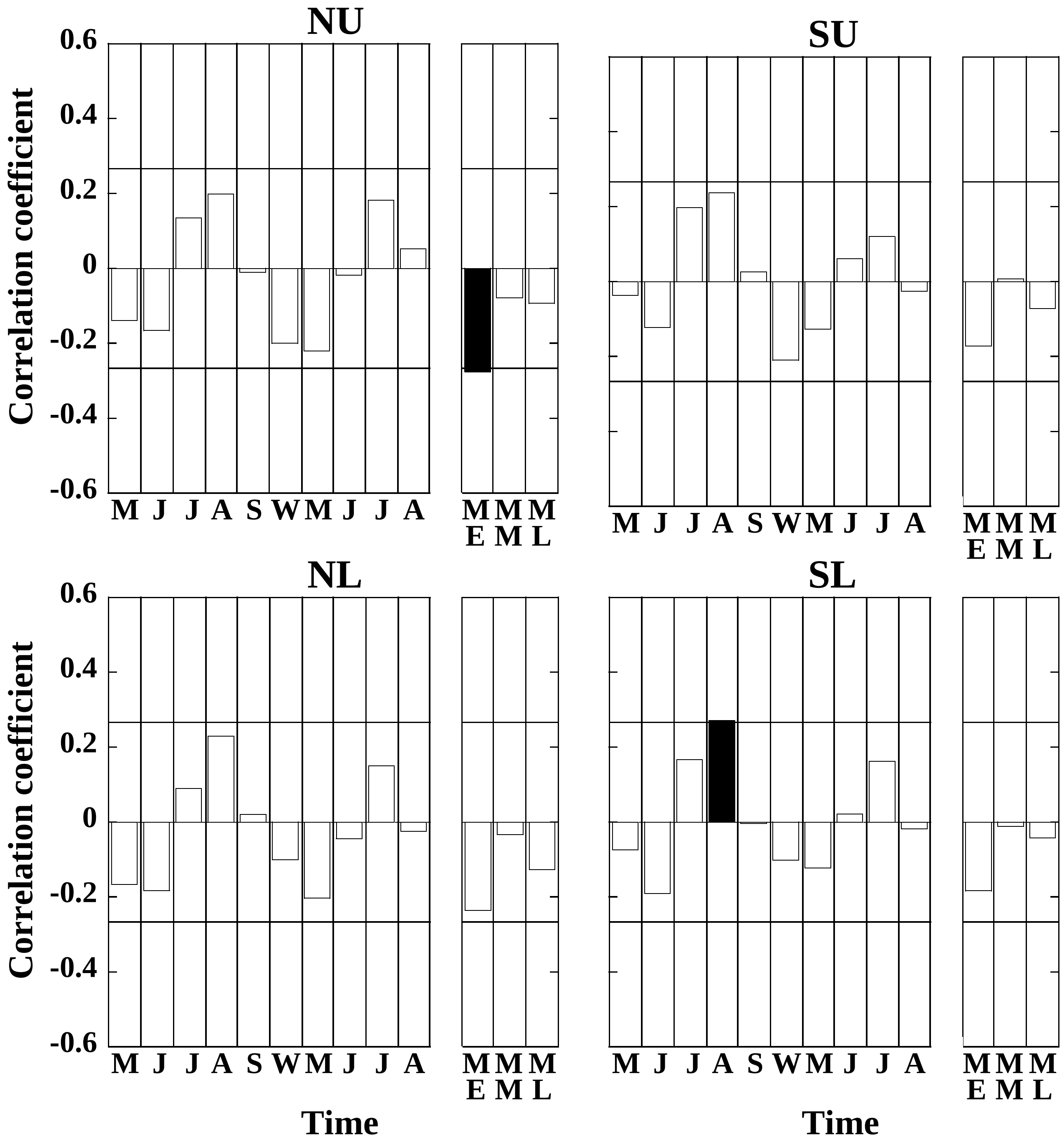
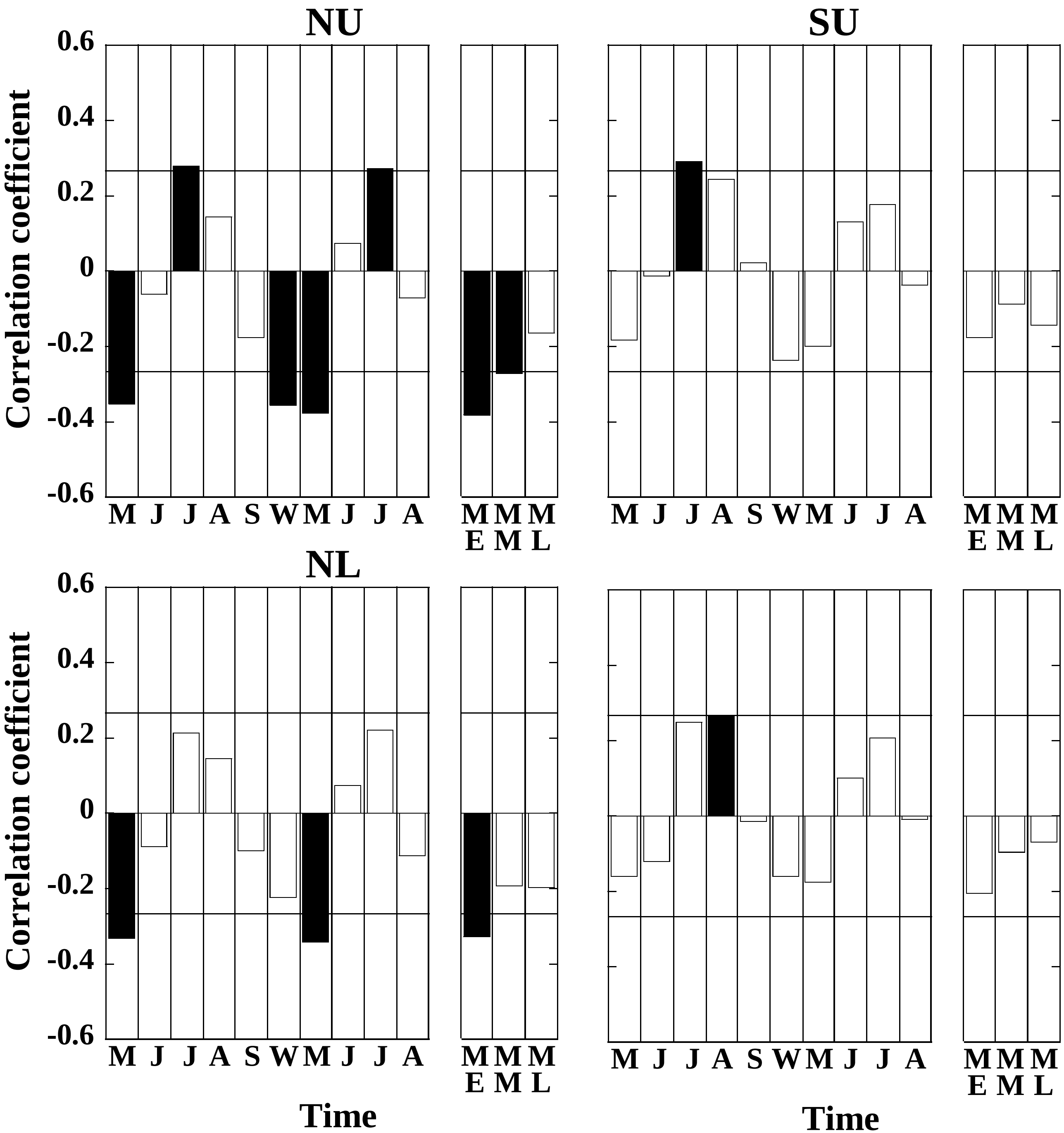
M J J A S O N D J F M A M J J A

Fig. 7



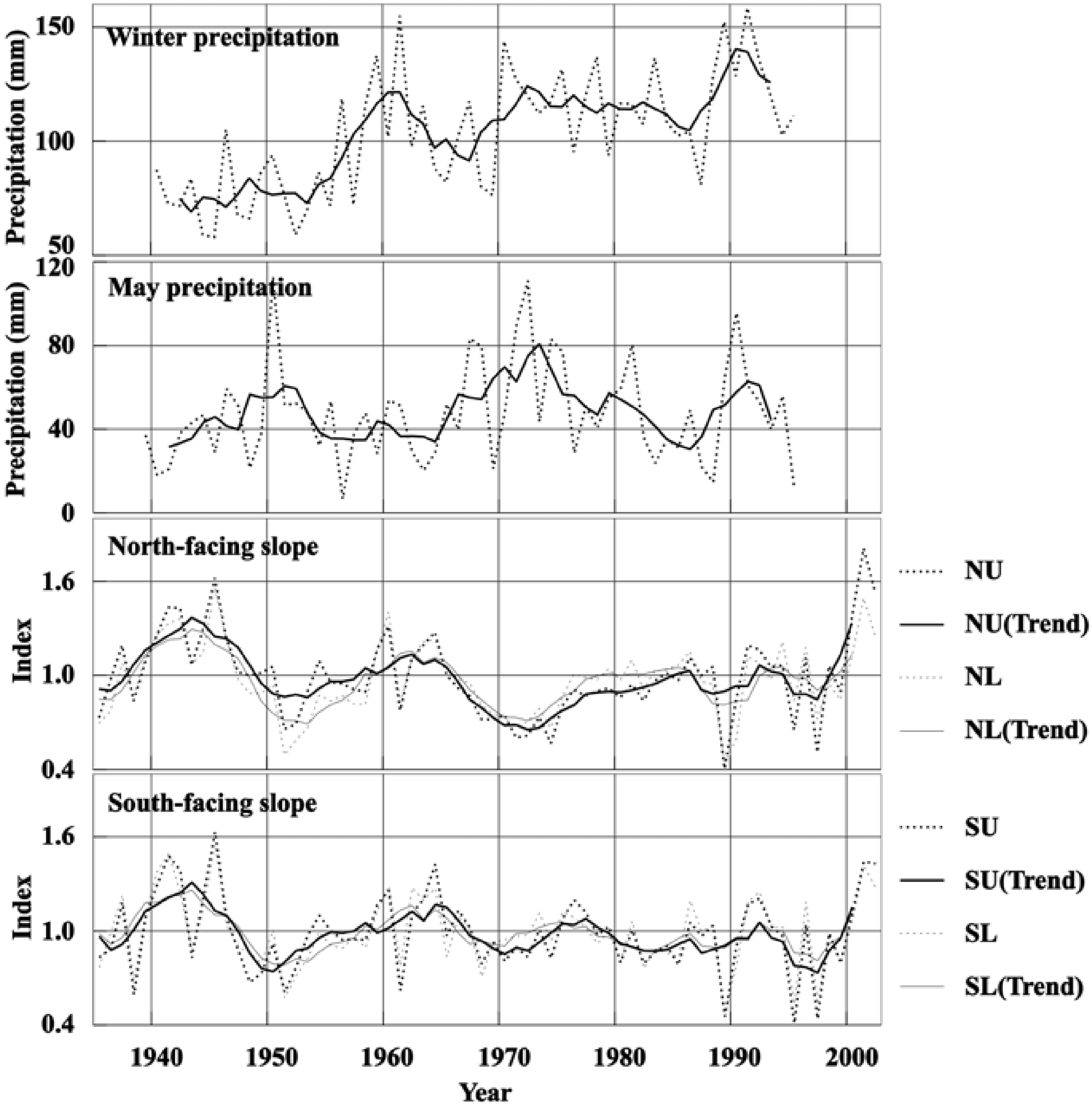
NU
SU
NL
SL
Correlation coefficient
Correlation coefficient
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
M J J A S W M J J A
M M M
E M L
Time
Time

Fig. 8



NU
SU
NL
Correlation coefficient
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
M J J A S W M J J A
M M M
E M L
Time

Fig. 9



Winter precipitation
May precipitation
North-facing slope
South-facing slope
Precipitation (mm)
Precipitation (mm)
Index
Index
150
100
50
120
80
40
0
1.6
1.0
0.4
1.6
1.0
0.4
1940
1950
1960
1970
1980
1990
2000
Year
NU
NU(Trend)
NL
NL(Trend)
SU
SU(Trend)
SL
SL(Trend)