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Temporal Changes in Growth–Climate Relationship of *Pinus taiwanensis* Hayata in Subtropical China

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Abstract: Whether the tree growth–climate relationship is consistent in subtropical China has not yet been reported. To fill this gap, we chose *Pinus taiwanensis* which grow on Lushan Mountain in a subtropical region of China as the target tree species, established a standard tree-ring width chronology, and conducted a moving correlation analysis with climatic factors. The results showed that the relationship between radial growth of *P. taiwanensis* and climate changed significantly during 1980–1990. From 1955 to 1985, tree rings were negatively affected mainly by precipitation in September of the current growing season. From 1990 to 2014, however, a significant negative correlation appeared between tree rings and sunshine duration from March to April in the growing season. Our results suggest the need to pay attention to this growth–climate inconsistency when conducting dendroclimatology studies in subtropical China. However, the causes of the inconsistency still require further confirmation.

Keywords: dendroclimatology; growth–climate relationship; subtropical; moving correlation; tree ring

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1. Introduction

Tree rings have been widely used as a proxy of paleo-climate reconstruction because of their high resolution and accurate cross-dating. Tree ring–based paleo-climate reconstructions have been extensively conducted globally, providing important evidence for our understanding of climate change [1–5]. However, the basic principle of homogeneity, which is the most important precondition for paleo-climate reconstruction [6], has been challenged with regard to tree rings due to the unstable relationships between tree rings and climate.

On the one hand, with climate change, the limiting factors of tree growth have changed, leading to an inconsistent growth–climate relationship, which is called the "divergence problem" [7]. For example, Briffa et al. [8] studied the relationship between the tree-ring width and late-wood density of several tree species and the climates in the high latitudes of the Northern Hemisphere and found that the sensitivity of tree growth to climate is decreasing. Recently, similar discoveries have been made in some mid-latitudes, such as in the European region [9–11] and Asia [12,13].

On the other hand, studies have shown that tree age also significantly affects growth–climate relationships. For example, Carrer and Urbinati [14] studied the corresponding relationships among four age classes of two tree species (*Larix decidua* Mill. and *Pinus cembra* L.) and the climate near the tree line of the Italian Alps and found that older trees had a stronger response to climate. Similar findings have been reported in European [15–17] and Asian [18–20] regions. These findings remind dendrochronologists to carry out stability tests first when performing reconstruction in order to verify that the growth–climate relationships are consistent.

Recently, with the vigorous development of dendrochronology, people have started paying attention to the warm and humid subtropical monsoon region. The climate pattern of the subtropical monsoon region in China is affected mainly by the uplift of the Qinghai–Tibet Plateau [21]. Compared to other regions at the same latitude, it is warm and humid. In the past, there were relatively few paleo-climate reconstructions using tree rings. However, with the recent increase in field work, tree species and regions that are highly sensitive to climate have been found. For example, Duan et al. [22] reconstructed the winter (January to April) temperature variation in subtropical China using the tree-ring width of *Pinus massoniana* Lamb. and found that the Ural High ridge might be the cause of extreme cold in winter in subtropical China. Shi et al. [23] reconstructed precipitation from February to April in a subtropical region by using *P. massoniana* tree-ring width. Cai et al. [24] reconstructed the surface temperature during the growing season in the subtropical region by using the ring width of *P. taiwanensis*. Apart from these climate reconstructions, other tree-ring studies have been conducted. Liang et al. [25] reported that the growth of *P. massoniana* in subtropical China was affected mainly by competition, which was followed by the climate factor. They also found that with an increase in latitude, the effect of climate increased and the effect of competition decreased. Huang et al. [26] conducted a meta-analysis to study the tree ring–climate relationship of *P. massoniana* in 113 sample sites in subtropical China. They found that the growth of *P. massoniana* was affected by both temperature and precipitation. Su et al. [27] studied the tree rings of 10 tree species on the Yunnan-Guizhou Plateau and found that drought was the climatic factor that extensively restricted tree growth in this region. Yang et al. [28] collected tree-ring samples from two conifer species (*Pinus yunnanensis* Franch and *Pinus kesiya* Royle ex Gord) in Yunnan and determined that the tree ring–climate relationship changed with dry-to-humid gradients. Zuidema et al. [29] analyzed tree-ring samples throughout the tropics and found that dry season climate had the greatest impact on tree growth.

Although considerable results have been achieved in tropical and subtropical regions in recent years, whether the tree ring–climate relationship in this subtropical region is consistent has not yet been verified. To fill this gap, we collected tree-ring samples of *P. taiwanensis* in the Lushan area in subtropical China to verify the stability of the tree ring–climate relationship.

2. Materials and Methods

2.1. Study Area

The study area is located in the Lushan National Nature Reserve, Jiangxi Province, China. The area is influenced by the subtropical monsoon climate and has vertical zonal vegetation types. The low altitude comprises evergreen coniferous forest. The dominant tree species are *Lithocarpus glaber* (Thunb.) Nakai, *Castanopsis sclerophylla* (Lindl.) Schott, and *Cinnamomum camphora* (Linn.) Presl. High altitude contains deciduous broadleaved forest, with the dominant species being *Castanea henryi* (Skam) Rehd. et Wils., and a scattered distribution of coniferous forests, mainly *P. massoniana*, *Cunninghamia lanceolata* (Lamb.) Hook., and *P. taiwanensis*.

2.2. Meteorological Data

The meteorological data were downloaded from the National Meteorological Information Center of the China Meteorological Administration (http://data.cma.cn/, accessed on 9 July 2018). The nearest meteorological station to the sampling site was Lushan Meteorological Station, which was 5 km from the sampling site, and the altitude difference was within 100 m. The climatic data that were downloaded included six factors: monthly maximum temperature (Tmax), monthly minimum temperature (Tmin), monthly mean temperature (Tmean), monthly precipitation (Pre), monthly sunshine duration (SunD), and monthly relative humidity (RH). According to the Lushan station records (1955–2014), the annual mean temperature, annual cumulated rainfall, and annual cumulated sunshine duration recorded were 11.7 °C, 1943.2 mm, and 1758.7 h, respectively (Figure 1). Precipitation was concentrated in the summer. The trends of mean annual temperature (MAT), annual precipitation (MAP), annual sunshine hours (MAS), and mean annual relative humidity (MARH) from 1955 to 2014 are shown in Figure 2. It can be seen that from 1955 to 2014, the MAT increased significantly, and the MAS decreased significantly, while precipitation and relative humidity did not change significantly. The trends of monthly sunshine duration, monthly temperature, monthly precipitation and monthly relative humidity from 1955–2014 are shown in Appendix A, Figures A1–A4.

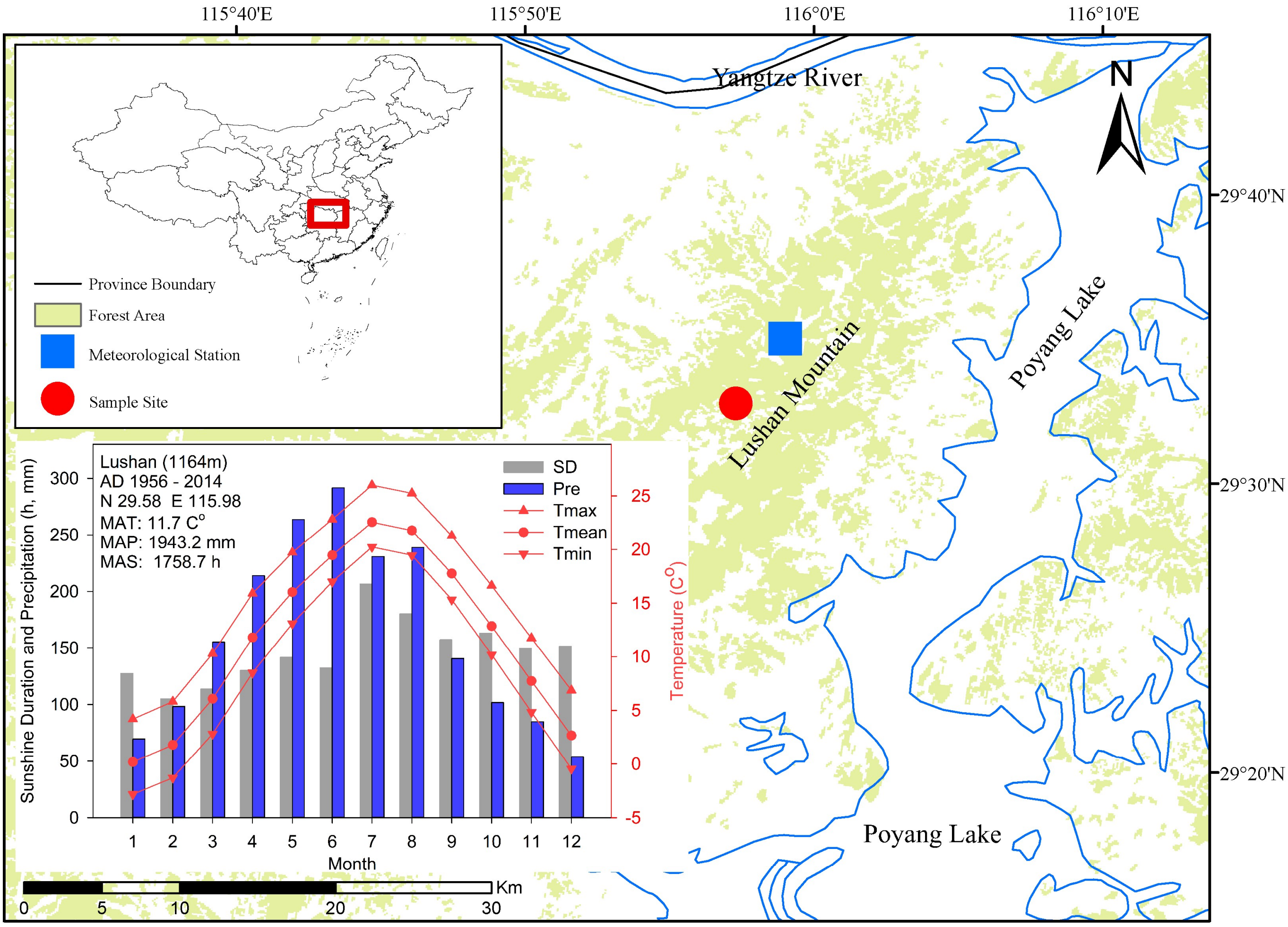

Figure 1. Sampling site and meteorological station locations and climate condition during 1955–2014 (small panel). MAT, mean annual temperature; MAP, mean annual precipitation; MAS, mean annual sunshine duration.

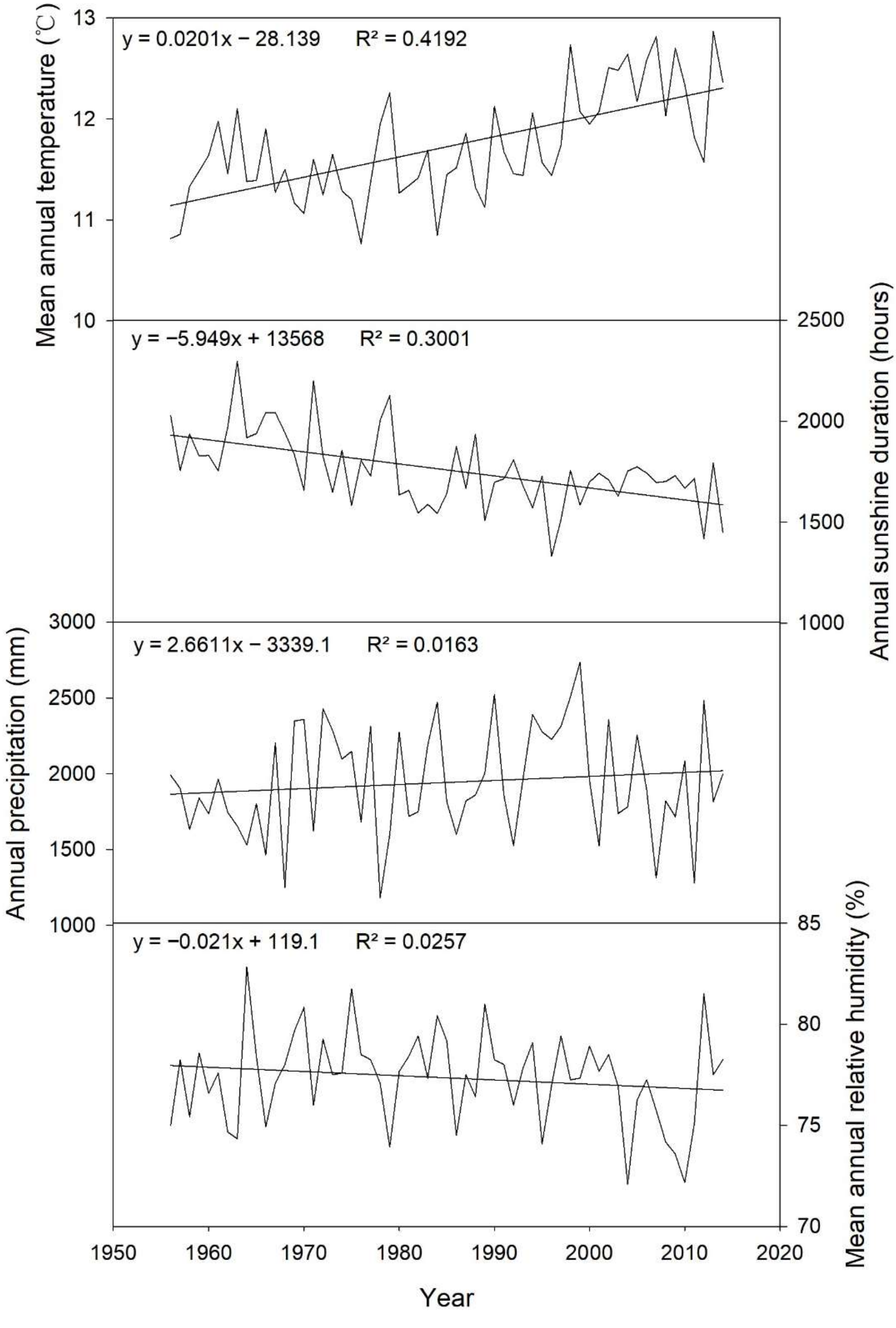

Figure 2. Trends of annual mean temperature, annual precipitation, annual sunshine hours, and annual mean relative humidity during 1955–2014.

2.3. Tree-Ring Data

P. taiwanensis, which is widely distributed in the subtropical center of China, was selected as the target tree species. It is endemic to China, living mainly in the subtropical region of China, and it is an important afforestation tree in the middle and lower reaches of the Yangtze River. Previous studies have also shown that the tree rings of this species are clear and accurately cross-dated and thus, they can be used in traditional dendroclimatology studies [24,30]. The fieldwork was carried out in 2015. The coordinates of the sampling sites were 29.55° N, 115.96° E, and 1055 m above sea level, and the slope was southward and less than 15° (Figure 1). According to the records of the Lushan Mountain Management Committee, the *P. taiwanensis* forest was planted artificially in the 1930s and then left in the natural state, without artificial care and destruction. Thus, it can be regarded as almost a natural forest without having experienced any human interference. Tree-ring increment cores (1–2 cores per tree) were drilled using an increment borer with an inner diameter of 5.12 cm at the height of 1.3 m of each tree trunk. Each sample core was as close to the pith of the tree as possible. In all, 36 cores were collected from 22 trees. The samples were brought back to the laboratory and carefully polished with 80–600 mesh sandpaper until the xylem cells were clearly visible. Then, the tree-ring widths of each core were measured using Lintab 6 with TSAP software (Version 4.81c, Frank Rinnthch, Germany). Finally, COFECHA was used to verify the cross-dating results to ensure that all data were accurate [31]. A cubic smoothing spline with a 50% frequency response cutoff that is equal to 32 years was used to remove the tree's own growth trend. Then, a bi-weight robust mean method was employed to build the final standard tree-ring width chronology (TRW). Common period analysis was conducted for the period of 1950–2014, and three statistical indices of correlation coefficients among all the series (rbar), expressed population signal (EPS), and signal–noise ratio (SNR) were calculated to quantify the quality of the chronology. All methods mentioned above were carried out using the "dplR" package of R software [32].

2.4. Statistical Analysis

The stability of the growth–climate relationship was verified by conducting a moving correlation analysis between TRW and climate factors during 1956–2014, with a 25-year window from October of the previous year to December of the current year. Bootstrap (1000 times) was used to ensure the production of stable results. A heat map was employed to show the final results. This analysis was carried out using the "treeclim" package of R software [33].

The results showed that the growth–climate relationship changed significantly during 1980–1990. Therefore, to further determine the specific transition year, we used climate data of different intervals to linearly fit the tree-ring width to identify the linear model with the best effect and to determine the exact year in which the response difference appeared. The period 1980–1990 was considered the boundary. Precipitation in September was considered the independent variable to fit TRW in the first half, while the mean sunshine duration from March to April was used to fit TRW in the second half. A linear regression was carried out with the "stats" package of R software [34].

To further confirm the growth–climate relationship inconsistency, correlation coefficients between TRW and climate factors during 1955–1985, 1986–2014, and 1955–2014 were calculated, respectively.

3. Results

3.1. Statistics of Chronology

The chronology covers a period of 86 years, from 1930 to 2015 (Figure 3, Appendix A, Table A1). The results of the common interval analysis showed that rbar, EPS, and SNR had values of 0.361, 0.941, and 15.99, respectively. Since 1939, the SSS value of chronology has been greater than 0.85, which indicates that the chronology during 1939–2014 is reliable [35,36]. Therefore, the results of subsequent analysis during 1956–2014 in this study are reliable.

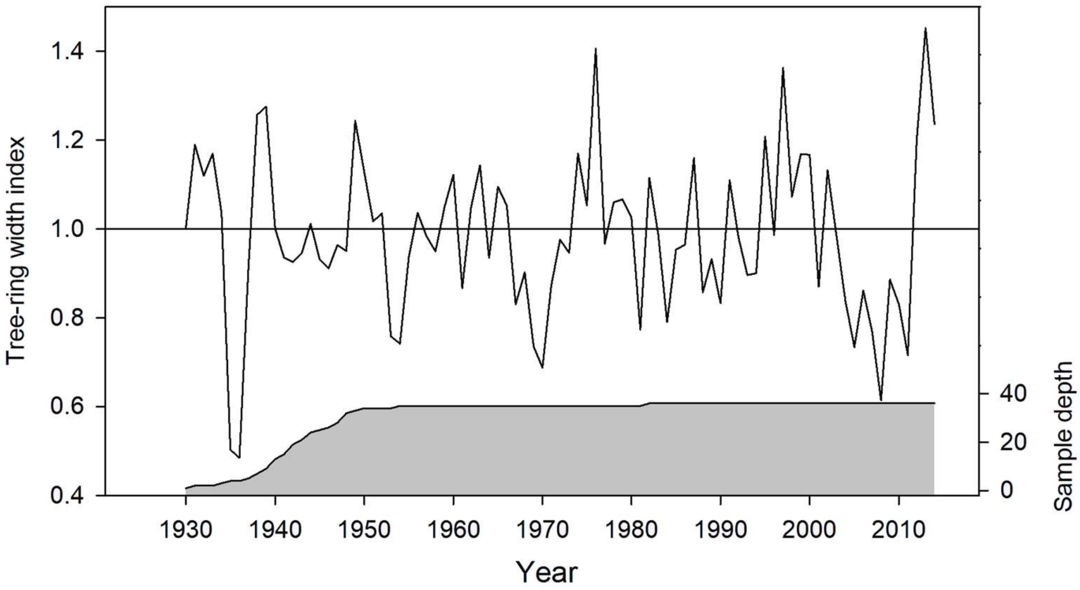

Figure 3. Tree-ring width chronology and sample depth.

3.2. Correlation Analysis Results

The results of the moving correlation analysis between the tree-ring and climate factors showed that the relationship between TRW and climate changed significantly during 1980–1990. The relationships between TRW and precipitation and sunshine duration were the most significant (Figures 4 and 5). Meanwhile, the relationship between tree ring and relative humidity also changed significantly, but the correlation coefficients were lower than those for precipitation and sunshine duration were (Figure 6). However, the mean maximum temperature, mean temperature, and mean minimum temperature had no meaningful influence on tree growth (not shown).

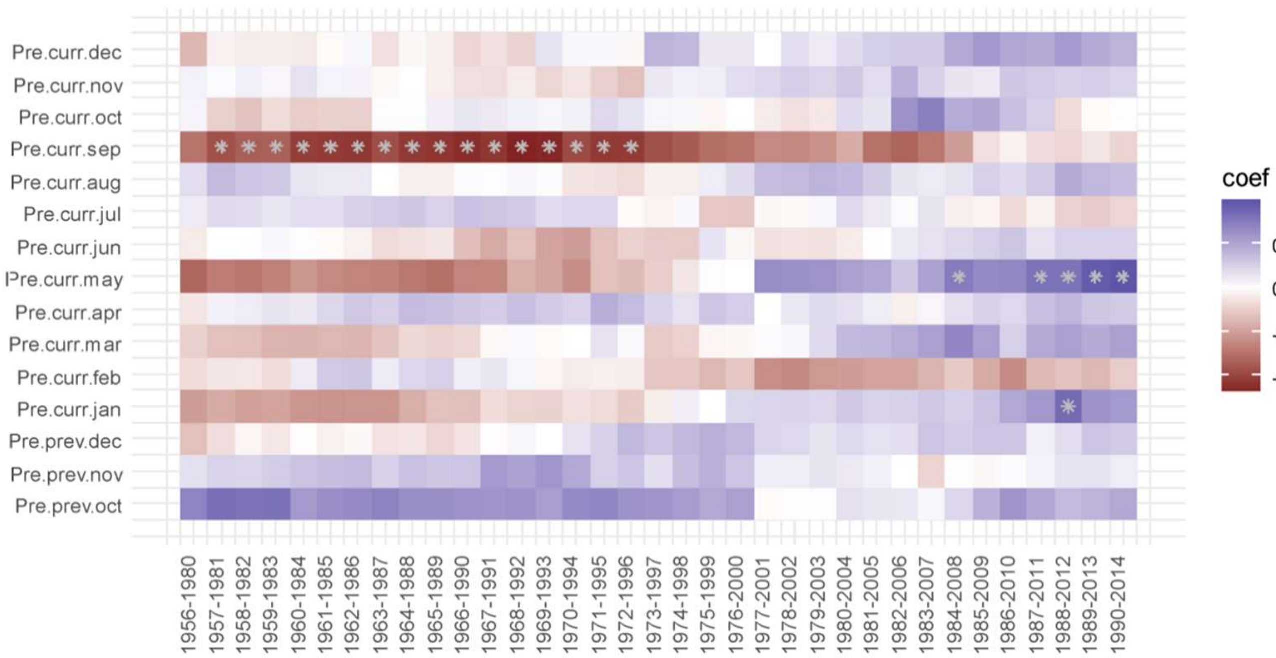

Figure 4. Moving correlation coefficients between tree-ring chronology and precipitation; prev. and curr. indicate previous and current years; * indicates significance at 0.05 level.

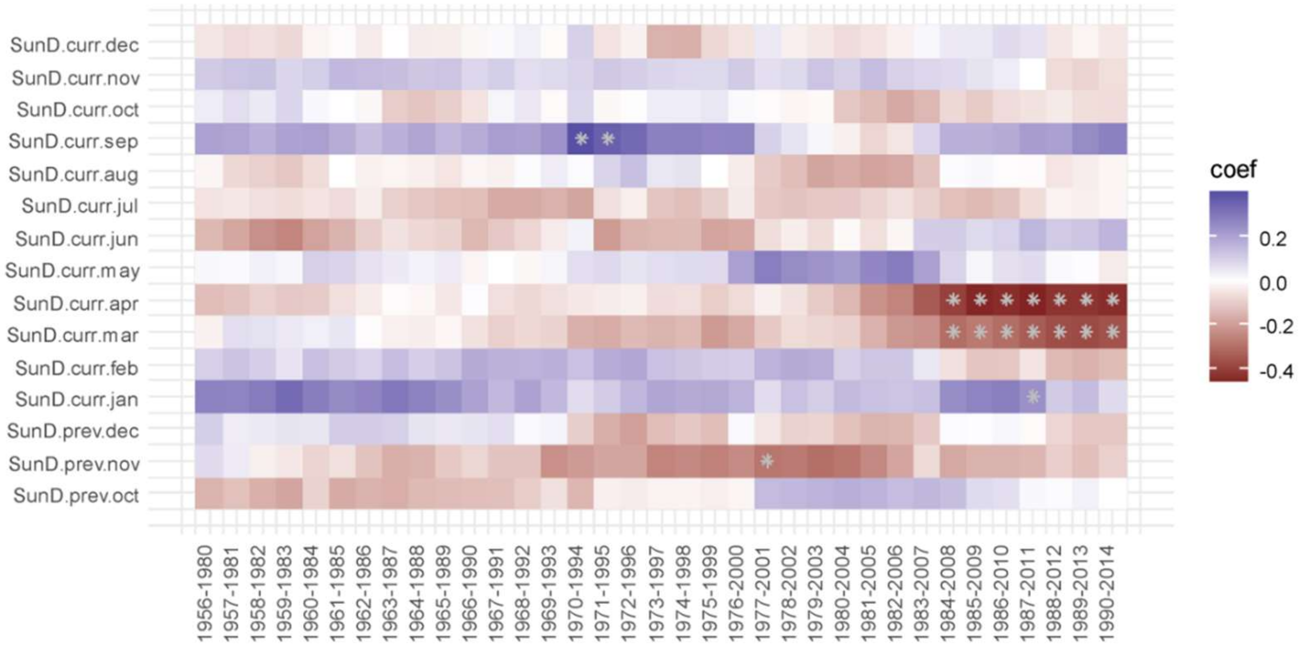

Figure 5. Moving correlation coefficients between tree-ring chronology and sunshine duration; prev. and curr. indicate previous and current years; * indicates significance at 0.05 level.

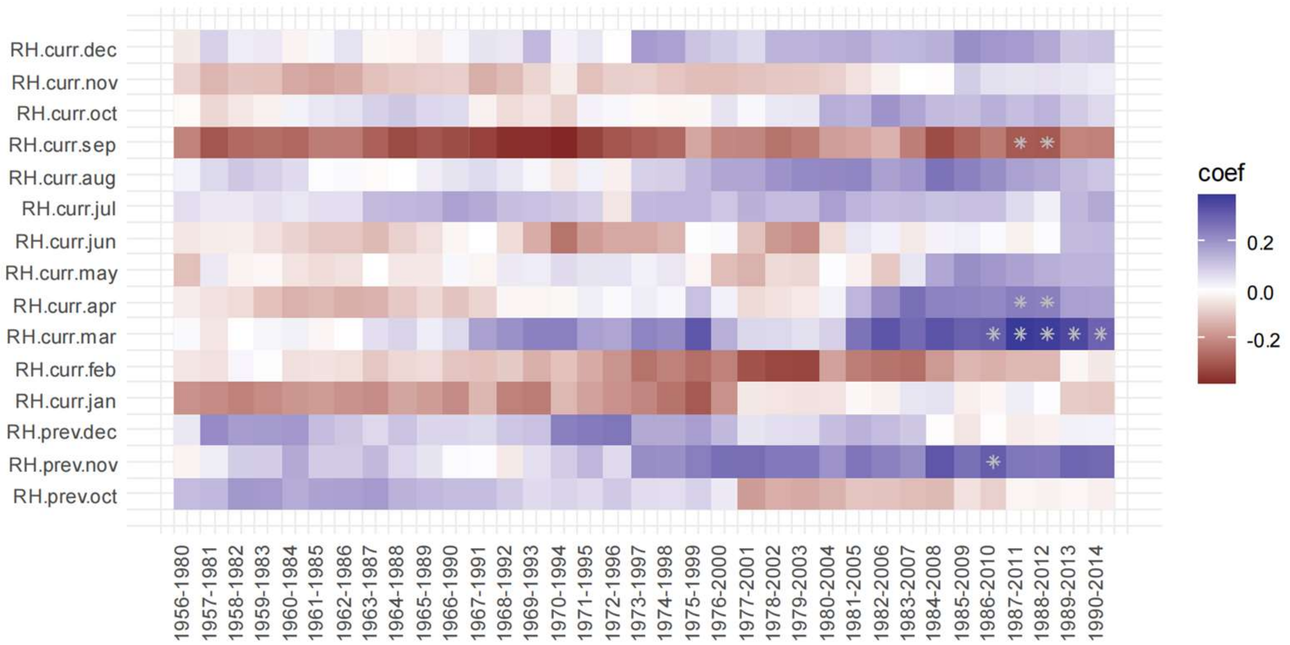

Figure 6. Moving correlation coefficients between tree-ring chronology and relative humidity; prev. and curr. indicate previous and current years; * indicates significance at the level of 0.05.

From 1956 to the 1980s, the tree rings were negatively affected by precipitation in the September of the current growing season. After that, the correlation between tree ring and precipitation in September disappeared, and a significant negative correlation appeared between tree ring and sunshine duration from March to April in the growing season (Figures 4 and 5). The results for relative humidity were similar to those for sunshine duration, with significantly positive effects on tree growth in March since the end of the 1980s (Figure 6). In addition, there has been a significant positive correlation between precipitation in May of the current growing season and tree rings since the end of the 1980s (Figure 4).

The growth–climate relationship from 1955 to 1985 showed that only the maximum temperature in the previous November had a significant limiting effect on tree growth (Appendix A, Figure A5). From 1986 to 2014, however, sunshine duration in March and April significantly inhibited tree growth, while precipitation in May and relative humidity in the previous November significantly promoted tree growth (Appendix A, Figure A6). Thus, the growth–climate relationships are completely different in the two time periods. While the growth–climate relationships during 1955–2014 were relatively complex and the tree rings exhibited a significant correlation with several climate factors, the coefficients were not high (Appendix A, Figure A7). The different relationships between TRW and climate factors that are shown in Appendix A, Figures A5–A7 confirm the inconsistent relationship between growth and climate over 1955–2014.

3.3. Linear Regression between TRW and Climate Factors

As the correlation coefficients between relative humidity and tree rings are lower than those for sunshine duration, relative humidity was not considered in the regression. The final results showed that the relationship between TRW and precipitation in September between 1956 and 1985 was the best fitted, with a correlation coefficient of −0.417 and explained variance of 0.174. The relationship between tree ring width and mean sunshine duration of March and April has increased significantly since 1990, and the variance that is explained has reached more than 0.4; indeed, the variance interpretation has reached 0.484 since 1995, indicating its suitability for paleo-climate reconstruction (Table 1). The two best-fitted models are shown in Figure 7.

Table 1. Linear regressions between tree-ring chronology and climate factors (precipitation of September and mean sunshine duration from March to April).

September Precipitation			Mean Sunshine Duration from March to April		
Time Span	***r***	**R-Square**	**Time Span**	***r***	**R-Square**
1956–1976	−0.379	0.144	1976–2014	−0.535	0.286
1956–1977	−0.380	0.144	1977–2014	−0.491	0.241
1956–1978	−0.390	0.152	1978–2014	−0.491	0.241
1956–1979	−0.398	0.159	1979–2014	−0.516	0.267
1956–1980	−0.400	0.160	1980–2014	−0.545	0.297
1956–1981	−0.354	0.125	1981–2014	−0.545	0.297
1956–1982	−0.362	0.131	1982–2014	−0.588	0.346
1956–1983	−0.359	0.129	1983–2014	−0.606	0.368
1956–1984	−0.416	0.173	1984–2014	−0.624	0.390
1956–1985	−0.417	0.174	1985–2014	−0.624	0.389
1956–1986	−0.413	0.170	1986–2014	−0.630	0.396
1956–1987	−0.389	0.151	1987–2014	−0.630	0.396
1956–1988	−0.410	0.168	1988–2014	−0.626	0.392
1956–1989	−0.412	0.169	1989–2014	−0.622	0.387
1956–1990	−0.414	0.172	1990–2014	−0.641	0.411
1956–1991	−0.407	0.166	1991–2014	−0.641	0.411
1956–1992	−0.407	0.166	1992–2014	−0.633	0.401
1956–1993	−0.392	0.153	1993–2014	−0.645	0.416
1956–1994	−0.376	0.141	1994–2014	−0.646	0.418
1956–1995	−0.413	0.170	1995–2014	−0.696	0.484

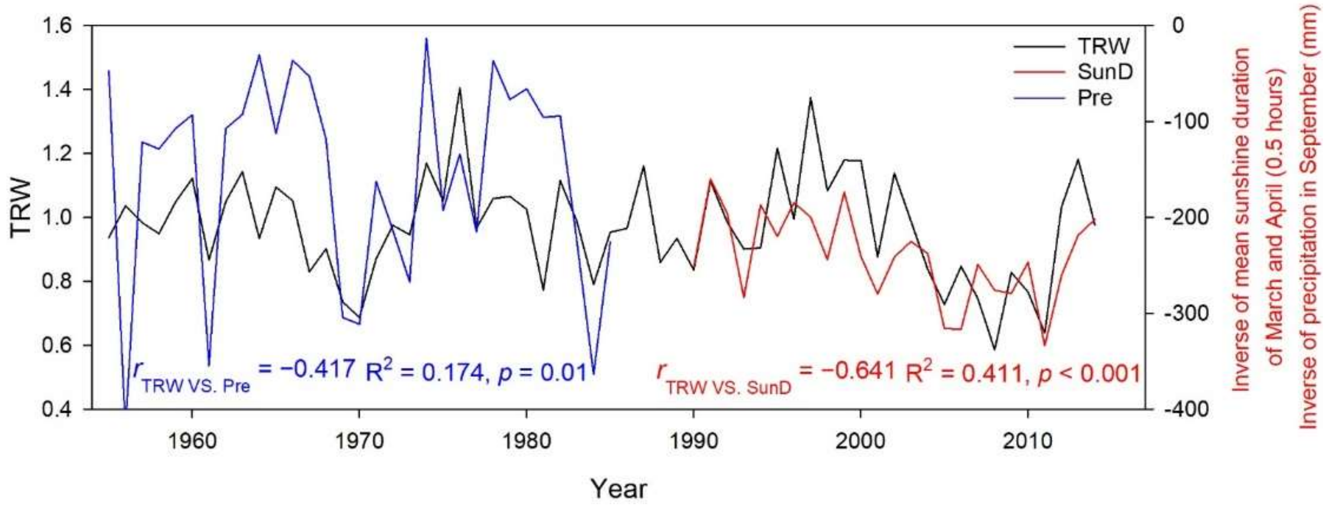

Figure 7. Best-fitted linear regression results. TRW, tree-ring width chronology; Pre, inverse of the precipitation in September; SunD, inverse of the mean sunshine duration of March and April.

4. Discussion

Our results showed that the tree growth–climate relationship changed significantly during 1985–1990. Many studies have shown the "divergence problem" in tree growth–climate relationships that are due to the abrupt climatic changes during the 1980–1990 period [7,37]. However, no significant change trends of the limiting climatic factors (precipitation in September and mean sunshine duration from March to April) were observed for 1985–1990 (Appendix A, Figures A1 and A3). Therefore, we think that the change in the relationship between *P. taiwanensis* and climate factors in subtropical China is not related to climate change.

Another possibility is that stand age had an effect on the growth–climate relationship. According to the forestry industry standard of the People's Republic of China—Regulations for age-class and age-group divisions of main tree species (LY/T 2908-2017)—the mature forest age of *P. taiwanensis* is between 41 and 60 years. Since the samples that were collected in this study were planted in around 1930, the age of the samples from 1985 to 1990 was approximately 50 years, which was the stage of transition from a near-mature forest to a mature forest. With the increase in tree age, the physiological and ecological processes of trees will change, resulting in the growth of trees in response to different environmental signals [14]. Therefore, we hypothesized that stand age might be the main factor leading to the change in the relationship between the growth of *P. taiwanensis* and climate. Similar results for age-altered growth–climate relationships have been found in many places for numerous tree species [15,16,18,20,38].

The results indicate that precipitation in September had a negative effect on tree growth during the young stage (1956–1985), which has also supported the previous findings that conifer trees in the subtropical region still have a growth peak from September to October [25,39,40]. The negative effects of precipitation play the following two roles. One is that precipitation leads to lower temperatures and reduced tree root activity, which affects the peak growth from September to October [3,17,41]. Another reason may be that more September precipitation means that a strong East Asian monsoon and a lot of low-level rainwater could cover the trees, which will reduce the photosynthetic active radiation, and thus narrowing the tree rings [25,28,42]. The latter can also be confirmed by the nonsignificant but stable positive correlation between sunshine and tree rings from 1956 to the 1980s. A similar finding was reported regarding the relationship between *P. massoniana* and September precipitation in a large region of subtropical China [25].

After *P. taiwanensis* has matured (i.e., after 1990 here), sunshine duration in March–April became the main limiting factor. This is possibly because, at the beginning of the growing season, water conditions are very important. When sunshine duration is longer, evaporation may increase. At this time, the East Asian monsoon has not started, and it is difficult to replenish moisture, resulting in a water shortage affecting the subsequent growth of trees. This can be well-proved by the correlation between relative humidity and tree rings (Figure 5). Similar findings have been found in the monsoon regions [23,43,44].

In addition, there is a closer relationship between climate and the mature forests of *P. taiwanensis*. The conclusion that older trees are more sensitive to climate has been reported previously [14,45–47]. A possible cause of this is due to the competition condition. In subtropical regions, the climate is suitable, and the growth rate of young stands is faster; thus, the competition might be relatively strong [25]. After maturity, with the closure of the forest, the competition pattern remains stable. As individual trees are larger, their demand for climate resources (i.e., light and water) increases, which leads to a greater sensitivity to climate change [48].

5. Conclusions

Our results show that the correlation between P. taiwanensis and climate factors in subtropical China changed significantly during 1985–1990. This change suggests the need to pay attention to this growth–climate inconsistency when conducting dendroclimatology studies in subtropical China. While the causes of the inconsistency still require further confirmation. In addition, the negative effect of spring sunshine duration on tree growth suggested that humidity may be the main driver of mature forest growth. Given the lack of humidity data, soil moisture monitoring in both mature and young stands is a feasible research topic in the future.

Author Contributions: Conceptualization and methodology, H.L., Z.W. and J.H.; performed the experiments, H.L., C.Z. and S.J.; manuscript writing, H.L., Z.W. and C.Z.; review and editing, H.L., Z.W. and J.H.; supervision, J.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Values of standard tree ring width chronology.

Year	TRW	Sample Depth	Year	TRW	Sample Depth
1930	0.998957	1	1972	0.977521	35
1931	1.192125	2	1973	0.945807	35
1932	1.123558	2	1974	1.16978	35
1933	1.175056	2	1975	1.048711	35
1934	1.05426	3	1976	1.398248	35
1935	0.505486	4	1977	0.963854	35
1936	0.488438	4	1978	1.056816	35
1937	0.91265	5	1979	1.061208	35
1938	1.255427	7	1980	1.022838	35
1939	1.267796	9	1981	0.770513	35
1940	1.018137	13	1982	1.11466	36
1941	0.93703	15	1983	0.986659	36
1942	0.926429	19	1984	0.790929	36
1943	0.949574	21	1985	0.954859	36
1944	1.010751	24	1986	0.965173	36
1945	0.929943	25	1987	1.160598	36

Table A1. *Cont.*

Year	TRW	Sample Depth	Year	TRW	Sample Depth
1946	0.909081	26	1988	0.857617	36
1947	0.962927	28	1989	0.932668	36
1948	0.947237	32	1990	0.832178	36
1949	1.23344	33	1991	1.106878	36
1950	1.121501	34	1992	0.977515	36
1951	1.015939	34	1993	0.893167	36
1952	1.035711	34	1994	0.894887	36
1953	0.758882	34	1995	1.19978	36
1954	0.743368	35	1996	0.978716	36
1955	0.937655	35	1997	1.352266	36
1956	1.036171	35	1998	1.063549	36
1957	0.986152	35	1999	1.160516	36
1958	0.950814	35	2000	1.162281	36
1959	1.049728	35	2001	0.867065	36
1960	1.124773	35	2002	1.129707	36
1961	0.872579	35	2003	0.987388	36
1962	1.051172	35	2004	0.841395	36
1963	1.146505	35	2005	0.7391	36
1964	0.939582	35	2006	0.869069	36
1965	1.100443	35	2007	0.77514	36
1966	1.058614	35	2008	0.619257	36
1967	0.835391	35	2009	0.895106	36
1968	0.908211	35	2010	0.836877	36
1969	0.741137	35	2011	0.719122	36
1970	0.692645	35	2012	1.203209	36
1971	0.878336	35	2013	1.440285	36

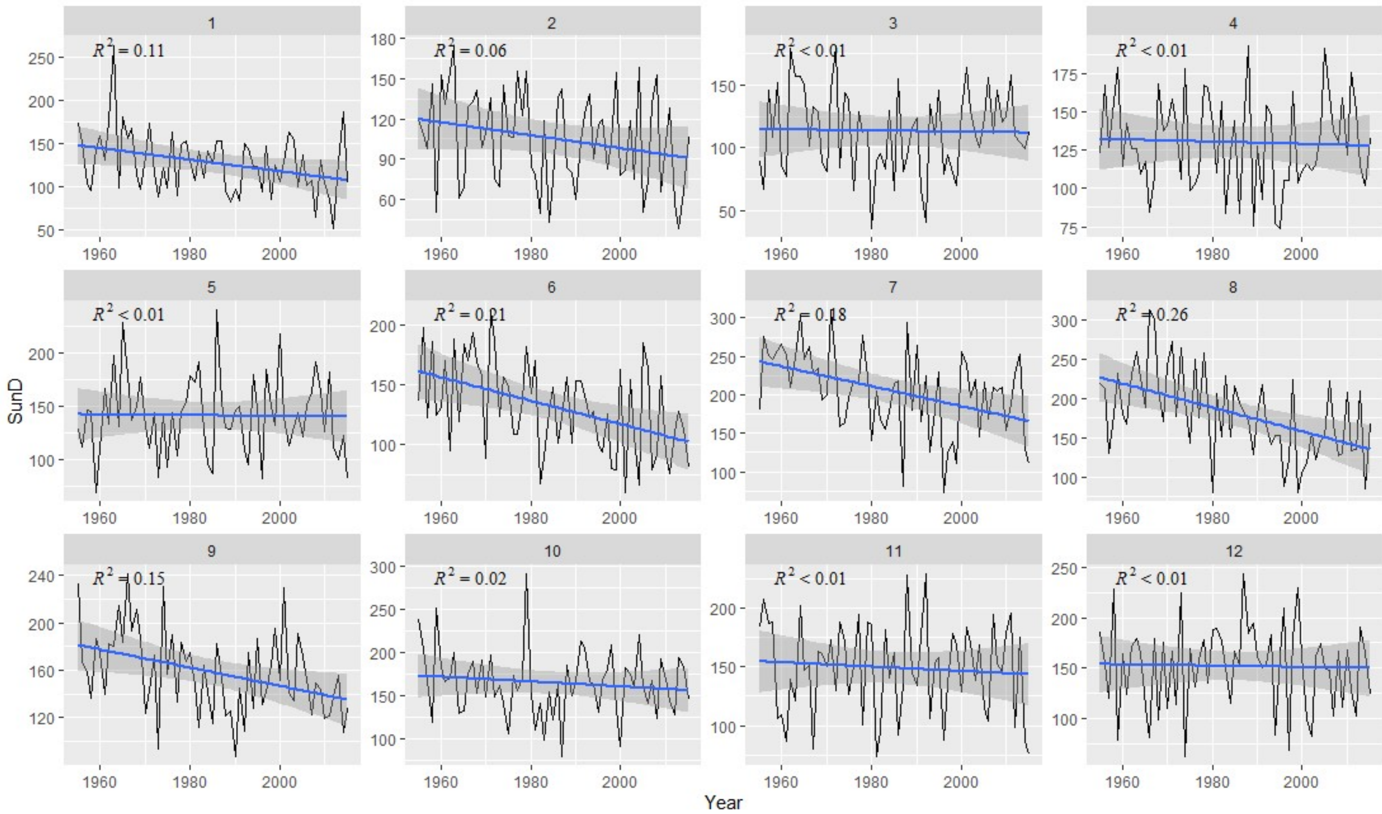

Figure A1. Climate trends of monthly sunshine duration during 1955–2014.

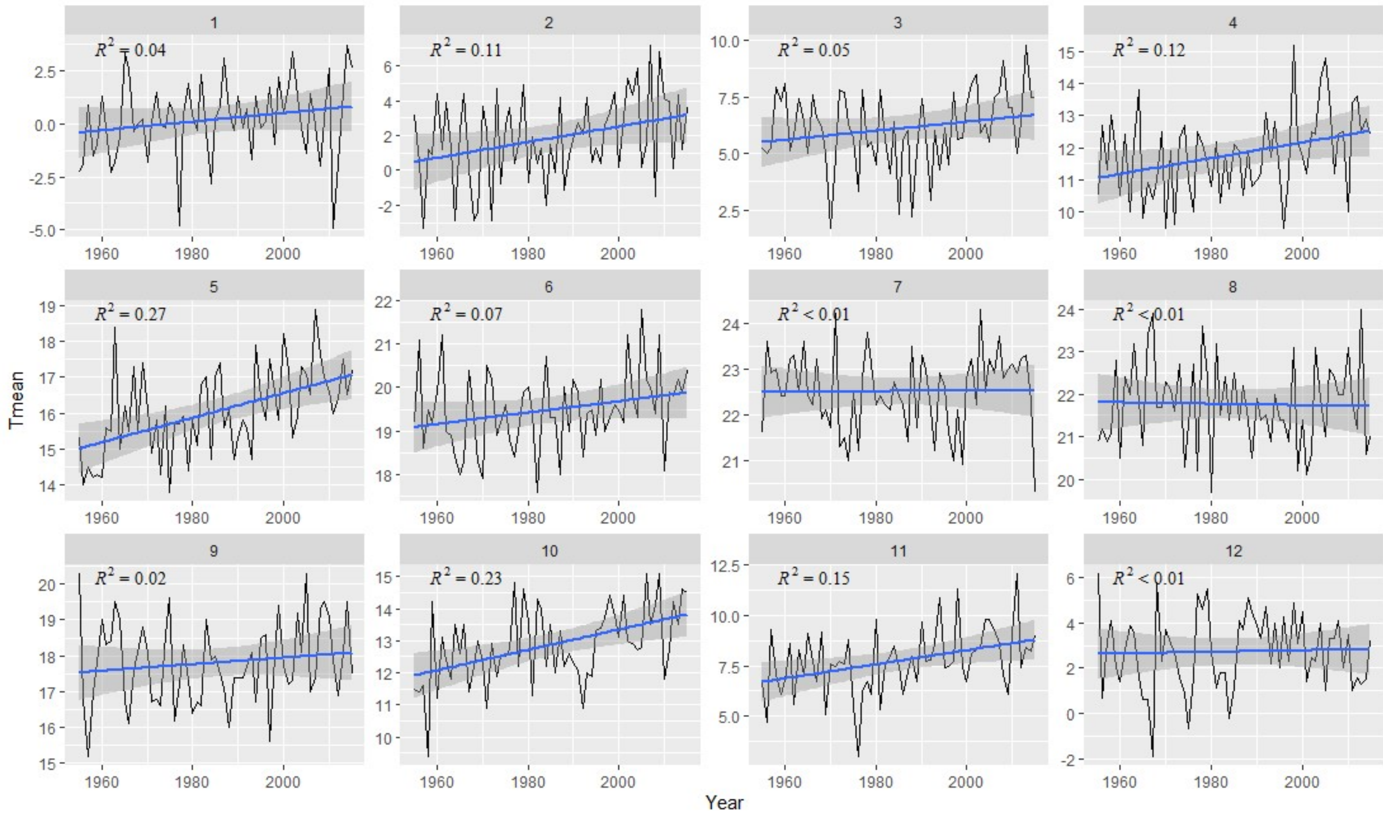

Figure A2. Climate trends of monthly temperature during 1955–2014.

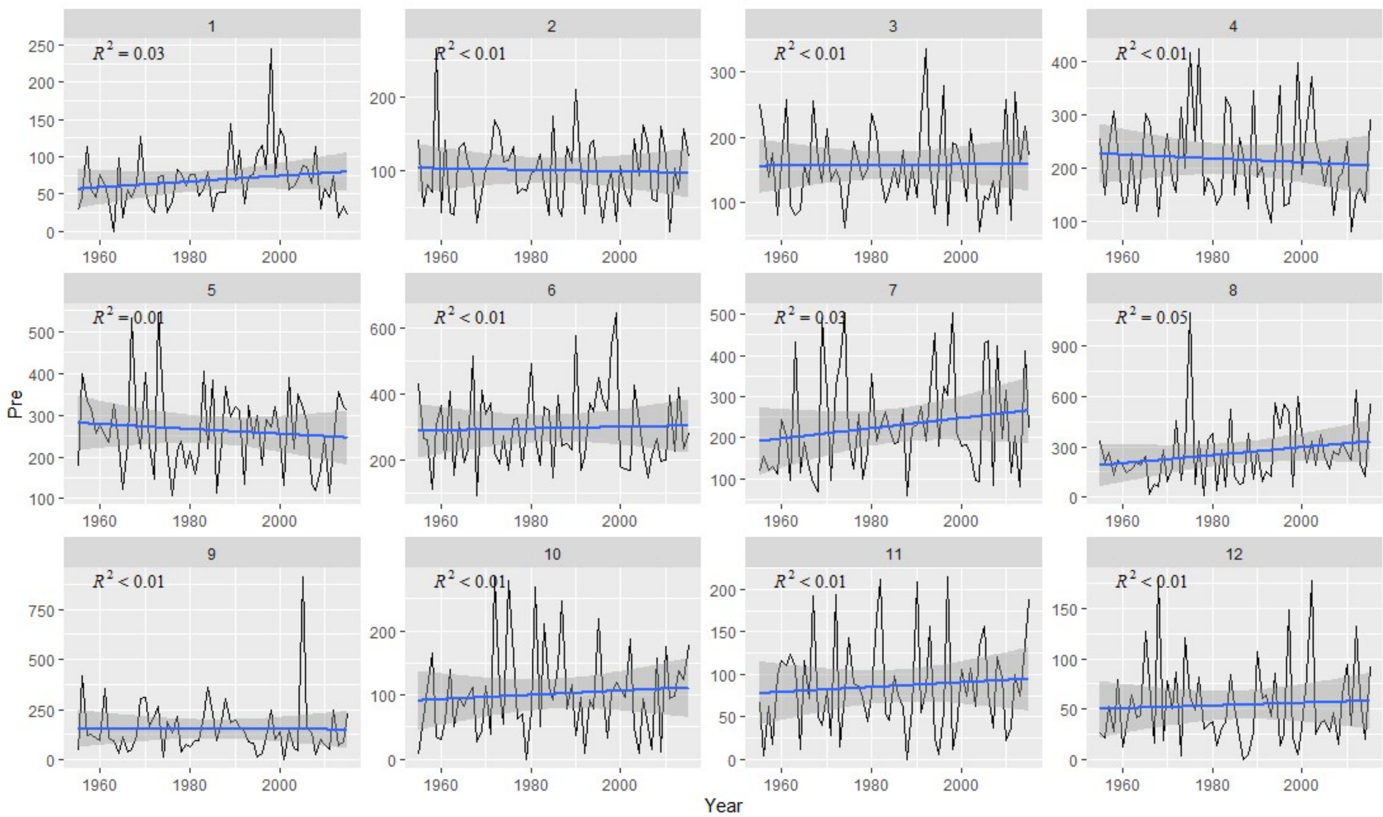

Figure A3. Climate trends of monthly precipitation during 1955–2014.

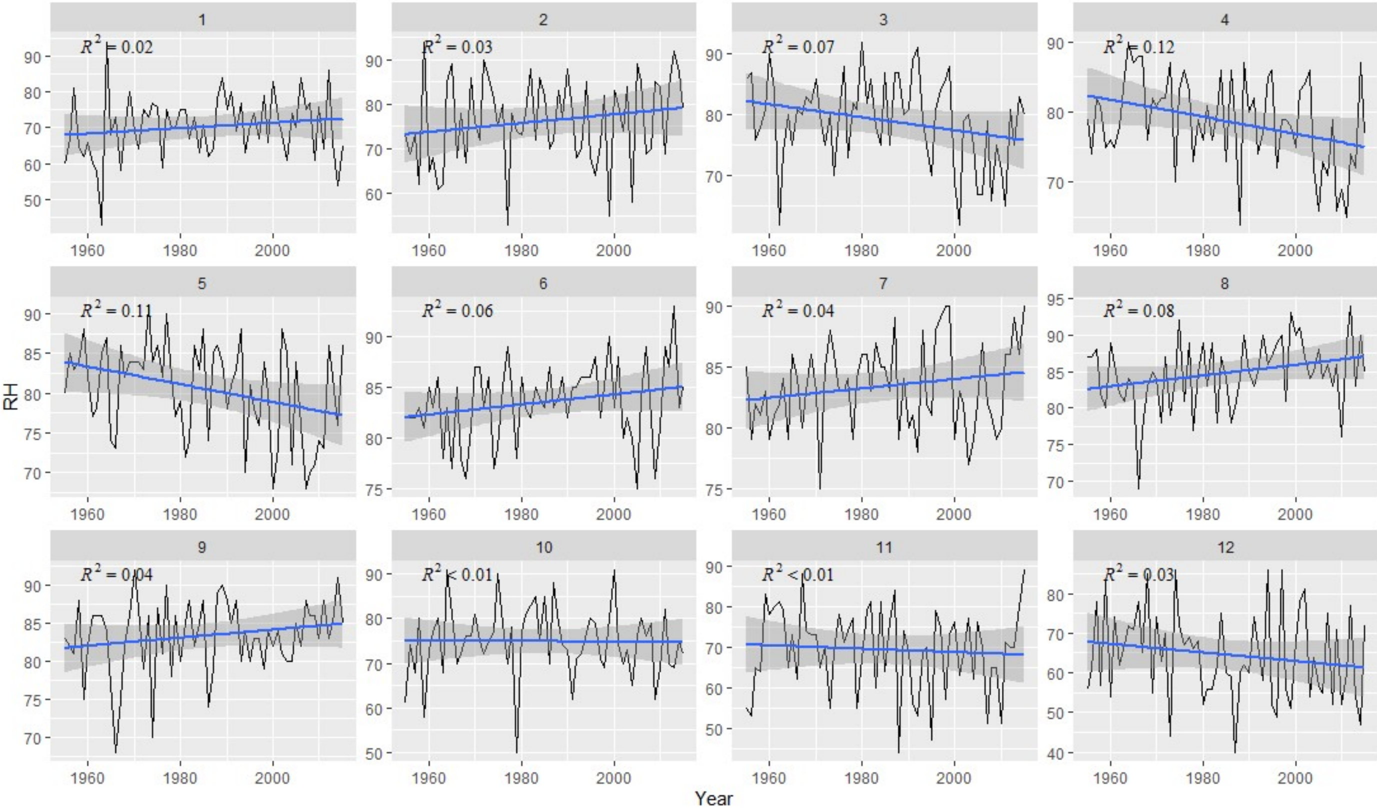

Figure A4. Climate trends of monthly relative humidity during 1955–2014.

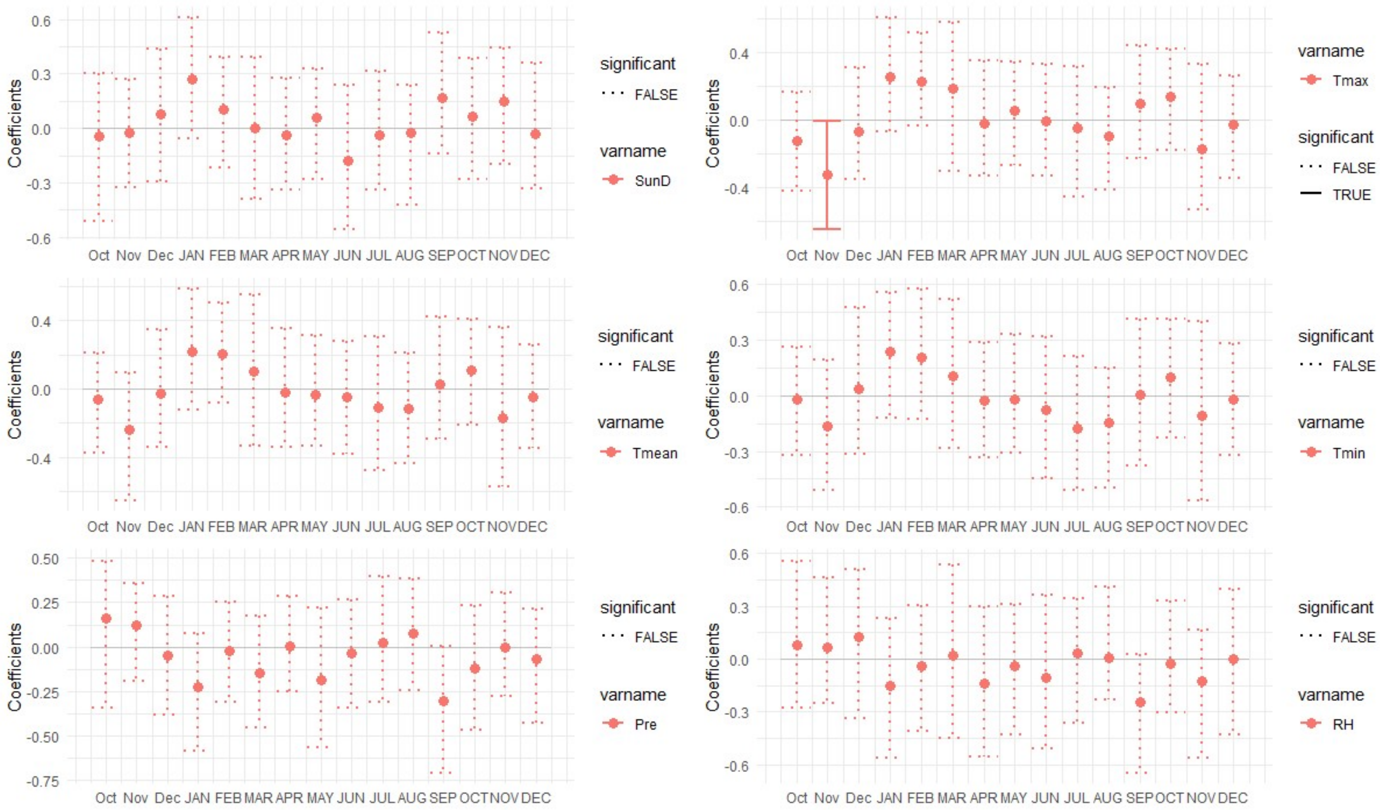

Figure A5. Correlation coefficient between TRW and climate during 1955–1985.

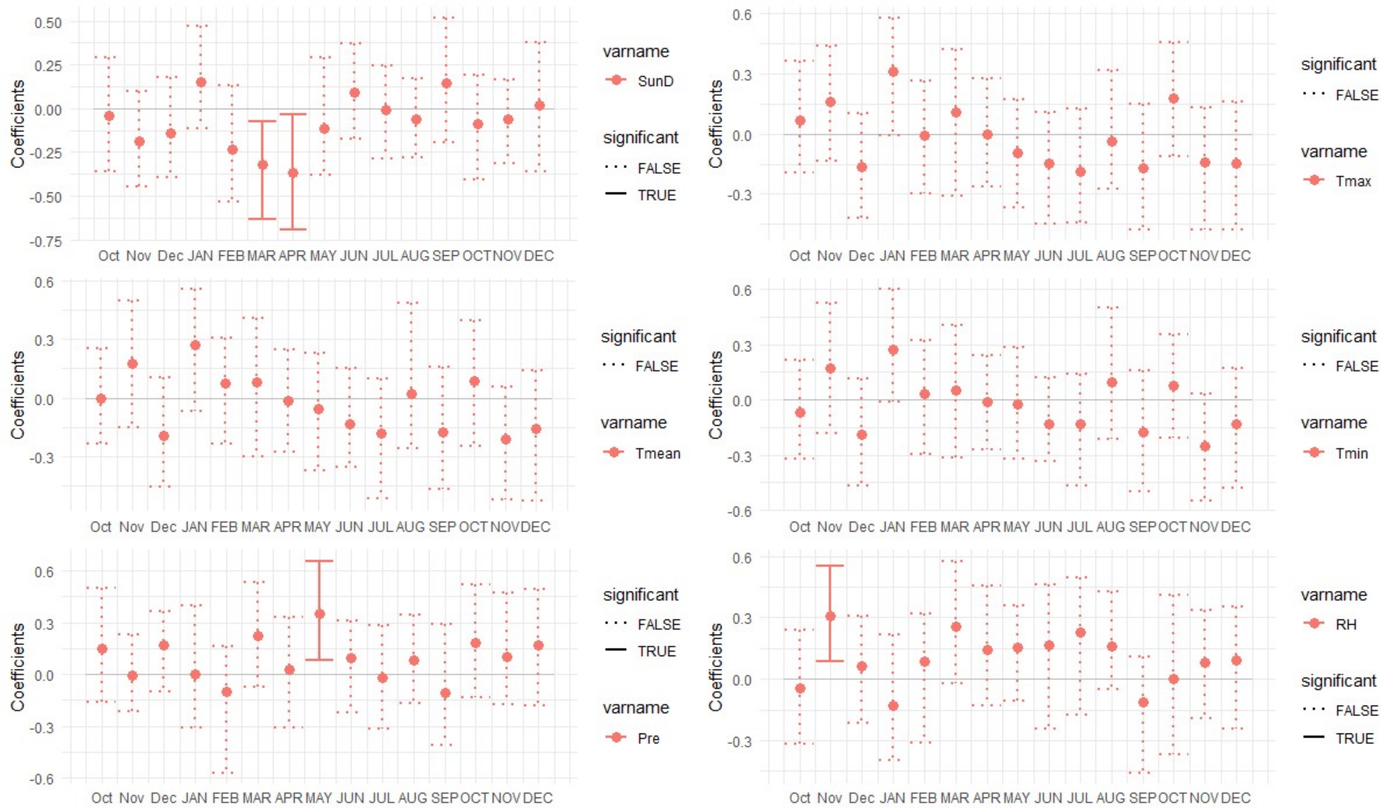

Figure A6. Correlation coefficient between TRW and climate during 1986–2014.

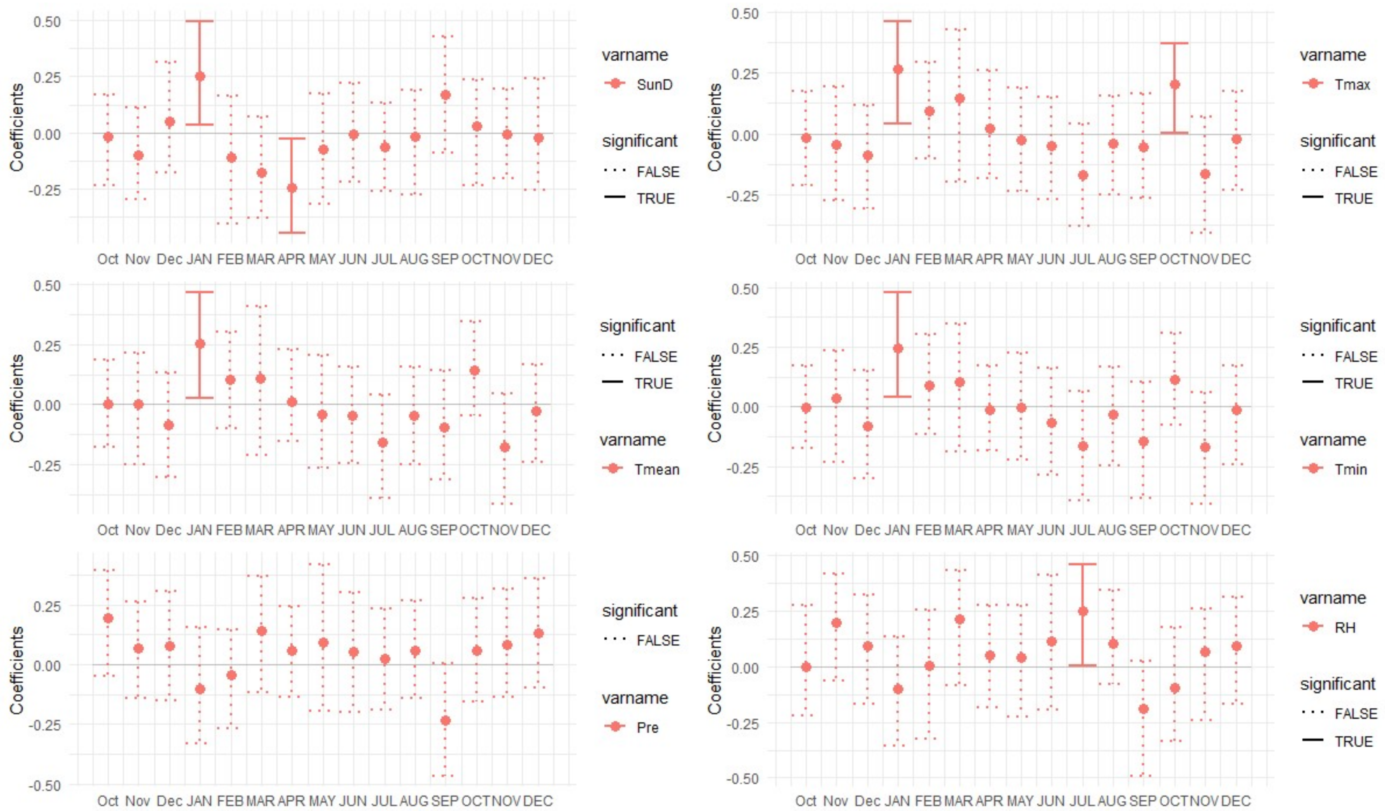

Figure A7. Correlation coefficient between TRW and climate during 1955–2014.

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