

Decreased Sensitivity of Tree Growth to Temperature in Southeast China after the 1976/'77 Regime Shift in Pacific Climate

(Penurunan Kepekaan Pertumbuhan Pokok terhadap Suhu di China Tenggara selepas Peralihan Rejim 1976/'77 dalam Iklim Pasifik)

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ABSTRACT

The climatic regime shift that occurred in the North Pacific Basin during 1976/'77 have been linked to a decadal mode of climate variability, which long-term behavior could be reconstructed from tree-ring records. We analyzed radial growth patterns of five subtropical tree species in Southeast China in relation to air and sea surface temperature, the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) indices 25 years before and after 1977. In 1953-1977, tree-ring chronologies showed higher correlations with air temperature than in 1978-2002, so that their time-series graphs showed divergence after 1977. The first principal component of the five tree-ring chronologies was significantly correlated with ENSO and PDO indices in 1978-2002, while it had no significant correlations with these variables during 1953-1977. Correlation maps of PC1, PDO and ENSO indices with surface air temperature showed different patterns before and after 1977. Based on these comparisons, altered sensitivity of tree growth to temperature in recent decades could depend on basin-wide climatic shift in the North Pacific, which either changed the effects of local climatic factors on tree growth or modified the relationships between local and regional climate.

Keywords: ENSO; PDO; temperature reconstruction; tree ring; 1976/77 regime shift

ABSTRAK

Peralihan rejim iklim yang berlaku di Lembangan Pasifik Utara semasa 1976/'77 telah dihubungkan dengan mod dekad kepelbagaian iklim, dengan kelakuan jangka masa panjangnya dapat dibina semula daripada rekod cecincin pokok. Kami menganalisis corak pertumbuhan cecincin spesies pokok subtropika di China Tenggara terhadap suhu udara dan permukaan laut, indeks Pacific Decadal Oscillation (PDO) dan indeks El Niño-Southern Oscillation (ENSO) selama 25 tahun sebelum dan selepas 1977. Pada 1953-1977, kronologi cecincin pokok menunjukkan korelasi tinggi terhadap suhu udara berbanding tempoh 1978-2002, oleh itu graf masa-siri menunjukkan percapahan selepas 1977. Prinsip komponen pertama bagi lima kronologi cecincin pokok didapati berkorelasi secara signifikan terhadap indeks ENSO dan indeks PDO pada 1978-2002. Namun, ia tidak menunjukkan korelasi secara signifikan terhadap pemboleh ubah ini bagi tempoh 1953-1977. Peta korelasi bagi indeks PC1, PDO dan ENSO terhadap suhu permukaan udara menunjukkan corak yang berlainan sebelum dan selepas 1977. Berdasarkan perbandingan ini, sensitiviti terubah pertumbuhan pokok terhadap suhu dalam dekad kebelakangan ini mungkin bergantung kepada peralihan iklim keseluruhan lembangan di Pasifik Utara dan ia telah mengubah kesan faktor iklim tempatan terhadap pertumbuhan pokok atau mengubahsuai hubungan antara iklim tempatan dan iklim serantau.

Kata kunci: Cecincin pokok; ENSO; PDO; pembinaan semula suhu; peralihan rejim 1976/77

INTRODUCTION

Pacific ocean-atmosphere variability on decadal-to-interdecadal time scales can have profound influences on ecosystems (D'Arrigo & Wilson 2006; Hoerling & Kumar 2003; López et al. 2006; Schöngart et al. 2004; Villalba 2007). Features of El Niño-Southern Oscillation (ENSO) events generate ecosystem responses, including signals in tree-ring chronologies (Andreu et al. 2007; D'Arrigo & Wilson 2006; Frank et al. 2005; López et al. 2006; Schöngart et al. 2004). During the 1976/77 winter season, the ocean-atmosphere system in the North Pacific Ocean displayed an abrupt state change (Miller et al. 1994). The

climatic regime shift of 1976/77 is now considered part of ENSO-like interdecadal variability in the extratropical Pacific basin (Frauenfeld et al. 2005) and is often referred to as the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997). Subsequent research has suggested that this event was not unique in the historical record but merely the latest in a succession of climatic regime shifts (Biondi et al. 2001; D'Arrigo & Wilson 2006). PDO has exhibited more frequent cold events and a slightly stronger sea level pressure gradient across the North Pacific from the mid-nineteenth to twentieth centuries (Trenberth & Hoar 1997; Tudhope et al. 2001). Some studies have suggested that

another PDO regime shift occurred in the late 1980s-early 1990s, although this later event differed from 1976/77 in terms of its climatic and ecosystem characteristics (Alheit et al. 2005; Rodionov & Overland 2005).

Decadal climatic regime shifts in the North Pacific have far-reaching impacts on both physical and biological systems over East Asia and North America (Caso et al. 2007; D'Arrigo et al. 2001; Mantua et al. 1997). Lo and Hsu (2008) showed a regime shift in temperature since the early 1950s in Taiwan and East Asia which could reflect the influence of PDO on the Asian monsoon. Zhang et al. (2008) reported that the sign of the correlation between the Asian monsoon and temperature switched around 1960s in northwest China, possibly causing both warming and lower monsoonal rains. Changes in rainfall and temperature variation over China in the late 1970s have been linked to the 1976/77 regime shift (Chang et al. 2000; Gong & Ho 2002; Hu 1997). These studies provide valuable insight for evaluating whether recent climate changes are unique in their spatial and temporal characteristics or within the range of natural variability (Biondi et al. 2001; Wilson et al. 2007). At the same time, since temperature and precipitation influence tree growth, this interdecadal variability may impact the sensitivity of tree-growth to climatic and environmental factors (D'Arrigo et al. 2008; López et al. 2006).

Tree-ring records are useful in understanding both climate shifts and short/long-term environmental variation. Recently a number of studies have focused on temporal changes in temperature sensitivity of tree growth, mainly in the northern high latitudes (Briffa et al. 1998; Vaganov et al. 1999; Wilson & Elling 2004). Wilmking et al. (2004) argued that temperature has explained more variability in tree radial growth after 1950, which is contrary to previous findings (Bräuning & Mantwill 2004). Büntgen et al. (2005) found no indication of a temporal shift in climate-growth relationship over the periods 1864-1993 and 1934-2002, while other studies pointed out a divergent trend between tree growth and temperature during recent decades. Briffa et al. (1998) reported a reduced sensitivity of recent tree-growth to summer temperatures at high northern latitudes and a growth decrease associated with increasing summer temperature over the past 90 years was reported by Barber et al. (2000) as evidence of temperature-induced drought in a large portion of the North American boreal forest. Oberhuber et al. (2008) suggested that radial growth in timberline and tree line chronologies at Mt. Patscherkofel (Tyrol, Austria) diverged from the July temperature trend since the mid-1980s in association with climatic changes (low winter precipitation, late frost) and/or increasing drought stress on cambial activity. Büntgen et al. (2006) mentioned a similar mechanism for growth-climate response shifts in a long subalpine Norway spruce chronology in the European Alps. Delayed snow melt due to increasing winter precipitation (Vaganov et al. 1999), the nonlinear relationship between larch tree growth and summertime warming (Carrer & Urbinati 2006; Carrer et al. 2007) and growth limiting effects of enhanced ultra violet

radiation (UV-B) as a consequence of falling concentrations of stratospheric ozone (Briffa et al. 2004) have also been proposed to explain recent divergence between tree-ring chronologies and air temperature records.

A larger network of tree-ring chronologies can aid efforts to understand the influence and nature of climatic changes and test a possible relationship between regime shifts in Pacific climate and the instability of tree-ring width chronologies to temperature. In this paper we develop multi-species tree-ring width chronologies from China; examine interrelationships among the chronologies; quantify relationships of tree growth with local climate before and after 1977; and examine correlation with indices of Pacific sea surface temperature before and after the 1976/77 regime shift.

MATERIALS AND METHODS

SITE DESCRIPTION

This study was conducted at the Gutian Mountain National Nature Reserve of Zhejiang Province, in subtropical Southeast China (Figure 1). The site is part of the Huaiyu Mountains and the highest peak, Qingjian, is 1258 m a.s.l. Subtropical monsoon climate characterizes this region, with distinct seasonal variability each year. Monthly climate data were obtained from the weather station in Tunxi (29°18' N, 118°17' E, 143 m a.s.l.), about 80 km southwest of the study area, for the period 1953-2002 (Figure 2). Mean total annual precipitation is 1964 mm, while mean annual temperature is 15.3°C; July is the hottest month (average mean temperature 27.9°C) while June is the wettest (average total precipitation 322 mm). The mean annual frost-free period is 250 days, while the mean relative humidity is 92.4%. The geological subsurface is mainly Mesozoic acidic igneous rocks, which is often overlaid by red soil, yellow soil, red-yellow or boggy soil (Xu et al. 2005). The dominant vegetation type in Gutian Mountain National Nature Reserve changes with elevation, from subtropical evergreen forest dominated by *Pinus taiwanensis* Hayata over 700 m a.s.l. to mixed needle and broad-leaved forest at the mid to lower elevations, including *Pinus massoniana* Lamb., *Schima superba* Gardn. et Champ., *Castanopsis* spp. and *Cyclobalanopsis* spp. (Du et al. 2009).

Five tree species were sampled for dendrochronological analysis. *P. taiwanensis* (HSS) occurs at the higher elevations, usually as isolated individuals. *S. superba* (MH) is found in evergreen broad-leaved stands from mid to high elevations, in association with *Castanopsis eyrei* (TC) (Champ. ex Benth.) Tutch., *Cyclobalanopsis glauca* (Thunb.) Oerst. and *Daphniphyllum oldhamii* (Hemsl.) Rosenth. *P. massoniana* (MWS) is located in the mixed needle and broad-leaved forest at the mid to lower elevation, together with *S. superba*, *C. eyrei* and *D. oldhamii*. *Cunninghamia lanceolata* (Lamb.) Hook. (SM) was sampled in a valley plantation (Figure 1).

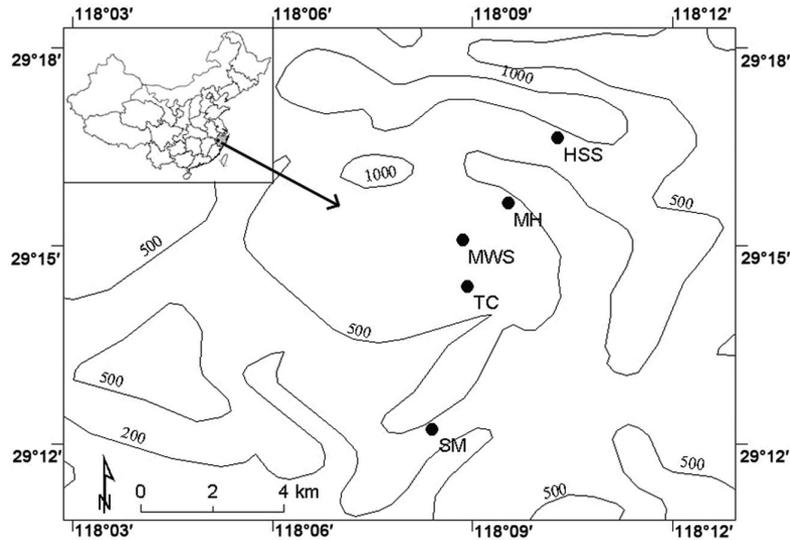


FIGURE 1. Contour map showing the locations of five tree-ring chronologies from Gutian Mountain, in southeast China. Site codes represent sampling sites of five tree species: HSS-*Pinus taiwanensis*, MH-*Schima superb*, MWS-*Pinus massoniana*, SM-*Cunninghamia lanceolata* and TC-*Castanopsis eyrei*



FIGURE 2. Climate diagram showing monthly mean air temperature and total precipitation at Tunxi weather station for the period 1953 to 2002

SAMPLE PROCESSING AND NUMERICAL ANALYSES

One core per tree was collected from the lower stem of relatively old trees. A total of 193 increment cores were collected at breast height from five tree species along an elevation gradient (Table 1). Increment cores were dried and mounted on wooden holders and were sanded with progressively finer grit sand papers (Figure 3). Tree-ring widths were measured to the nearest 0.001 mm with a TA Unislide measurement system (Velmex Inc., Bloomfield, New York). The measured tree-ring sequences were checked for crossdating by the COFECHA program (Holmes 1983) and errors were corrected following microscopic examination of the tree-ring cores. Cores that did not cross-date were not included in the analysis. We used the computer program ARSTAN to standardize ring-width sequences using a cubic smoothing spline function with 50% frequency response at 65% of the series length (Cook & Holmes 1986). This option is more appropriate than 'conservative' detrending because the sampled species grow in humid subtropical ecosystems, and are therefore not properly modeled by modified negative

exponential or straight line trends (Biondi & Qeandan 2008). Dimensionless tree-ring indices were computed as ratios between the ring-width measurement and the fitted spline curve. Standard master tree-ring chronologies were produced for each species using a biweight robust mean to reduce the effects of outliers. To assess the degree of similarity among chronologies, a principal component analysis (PCA) (Legendre & Legendre 1998) based on the correlation matrix was calculated for the common period 1922-2004.

Climate-growth relationships were quantified separately for the periods 1953-1977 and 1978-2002. Correlation functions were computed between the first principal component of the five tree-ring chronologies (as predictand) and monthly temperature and precipitation (as predictors) at the Tunxi station using the software program DENDROCLIM2002. This program uses 1000 bootstrap samples to evaluate statistical significance and stability of the correlation function coefficients (Biondi & Waikul 2004). As radial growth is influenced by climatic

TABLE 1. Summary characteristics of five tree-ring collection sites

Site	Species	Long. (E)	Lat. (N)	Elev. (m)	Cores*
HSS	<i>Pinus taiwanensis</i>	118°10'16.48'	29°16'37.49'	985	38(31)
MH	<i>Schima superba</i>	118°09'31.45'	29°15'38.39'	725	39(34)
MWS	<i>Pinus massoniana</i>	118°08'50.64'	29°15'04.62'	650	39(37)
SM	<i>Cunninghamia lanceolata</i>	118°08'54.86'	29°14'22.40'	356	46(29)
TC	<i>Castanopsis eyrei</i>	118°08'23.13'	29°12'12.94'	520	31(20)

* The cores collected (outside parentheses) and the cores used (inside parentheses) are both shown. Since one core per tree was collected, this is also the number of sampled trees

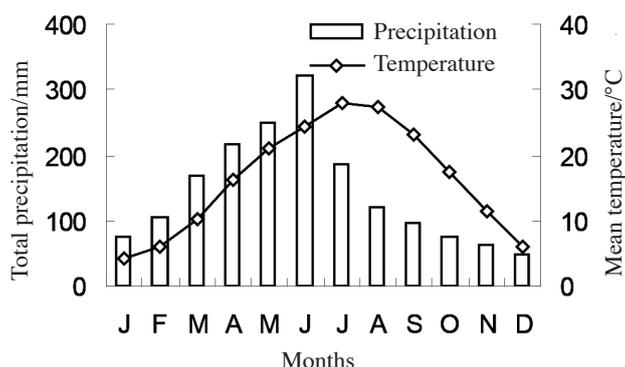


FIGURE 3. Photos of growth rings for the five sampling tree species

conditions several months before ring formation (Fritts 1976), we examined relationships over a 15-month period, from August of the previous growing season to October of the current year. Correlation analysis was conducted between the first principal component of the five tree-ring chronologies and the monthly PDO and ENSO (Niño 3.4 region) indices (Available from <http://www.cpc.ncep.noaa.gov/>) for the current year during the periods 1953-1977 and 1978-2002.

Synoptic analysis relied on correlation maps between Pacific SST indices (PDO and Niño 3.4) and gridded temperature data available from the NCEP/NCAR reanalysis web site for the period 1953-2002 (Kalnay et al. 1996). Influences of the 1976/77 regime shift on regional temperature and tree growth were studied by means of correlation maps for two 25-year periods, i.e. 1953-1977 and 1978-2002. Correlation maps were drawn using the KNMI Climate Explorer (<http://climexp.knmi.nl>) for the region covering 73-136°E longitude and 15-54°N latitude, which includes all of China and most of monsoon Asia. Correlation maps between PC1 scores of tree-ring chronologies and mean annual surface temperatures from the NCEP/NCAR reanalysis for the two 25-year periods were also drawn using the KNMI Climate Explorer (van Oldenborgh et al. 2009).

RESULTS

Numerical summaries of the tree-ring chronologies suggested that the five species are suitable for dendroclimatological studies (Table 2). *P. taiwanensis*

and *C. lanceolata* showed higher mean sensitivity, standard deviation and signal-to-noise ratio than the other species. Express population signals were greater than 0.85 (Table 2), except for *C. eyrei* (0.805). The first principal component (PC1) accounted for 25-46% of the variance in the site chronologies.

Correlations between tree-ring chronologies for their common 83-year period (1922-2004; Table 3) were higher between *P. taiwanensis* and *P. massoniana* ($r=0.68$, $p<0.0001$) than between other chronologies. Significant correlation coefficients among pairs of chronologies suggested a similar response to environmental changes in this region. This was reflected by the first two principal components of the five chronologies, which explained 50.6 and 21.1%, respectively (total 71.7%) of the variance.

Instrumental annual mean temperature at the Tunxi station (Figure 2) showed an increase in recent years. After transforming the tree-ring chronologies and the temperature record into standard deviation units, their graph showed a divergence after about 1977 (Figure 4). Linear correlations varied between the two periods, often switching from positive to negative (Table 4). Tree-ring indices were higher than mean annual temperature in the 1980s, but became lower in the most recent decade (Figure 4). Tree growth (PC1) usually showed positive correlations with monthly average air temperature in 1953-1977, while during 1978-2002 correlations were usually negative (Figure 5(a); no clear pattern emerged for precipitation (Figure 5(b)). On the other hand, correlations between PC1 and monthly sea surface temperature in the Niño 3.4 region

TABLE 2. Comparative statistics of the five tree-ring width chronologies

Site code	HSS	MH	MWS	SM	TC
First Year*	1818	1831	1827	1922	1919
Mean sensitivity	0.174	0.146	0.148	0.177	0.151
Standard deviation	0.281	0.197	0.200	0.222	0.178
Autocorrelation order 1	0.707	0.557	0.627	0.410	0.438
Signal-to-noise ratio	15.33	6.444	9.594	10.08	4.129
Express population signal	0.939	0.866	0.906	0.910	0.805
% Variance in first principal component	46.9%	25.3%	29.0%	32.9%	25.6%

* Last year is 2004 for all chronologies

TABLE 3. Correlation matrix between chronologies for their common 1922-2002 period (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$)

	HSS	MH	MWS	SM
MH	0.28**			
MWS	0.68***	0.34**		
SM	0.22*	0.35***	0.23*	
TC	0.35***	0.46***	0.40***	0.50***

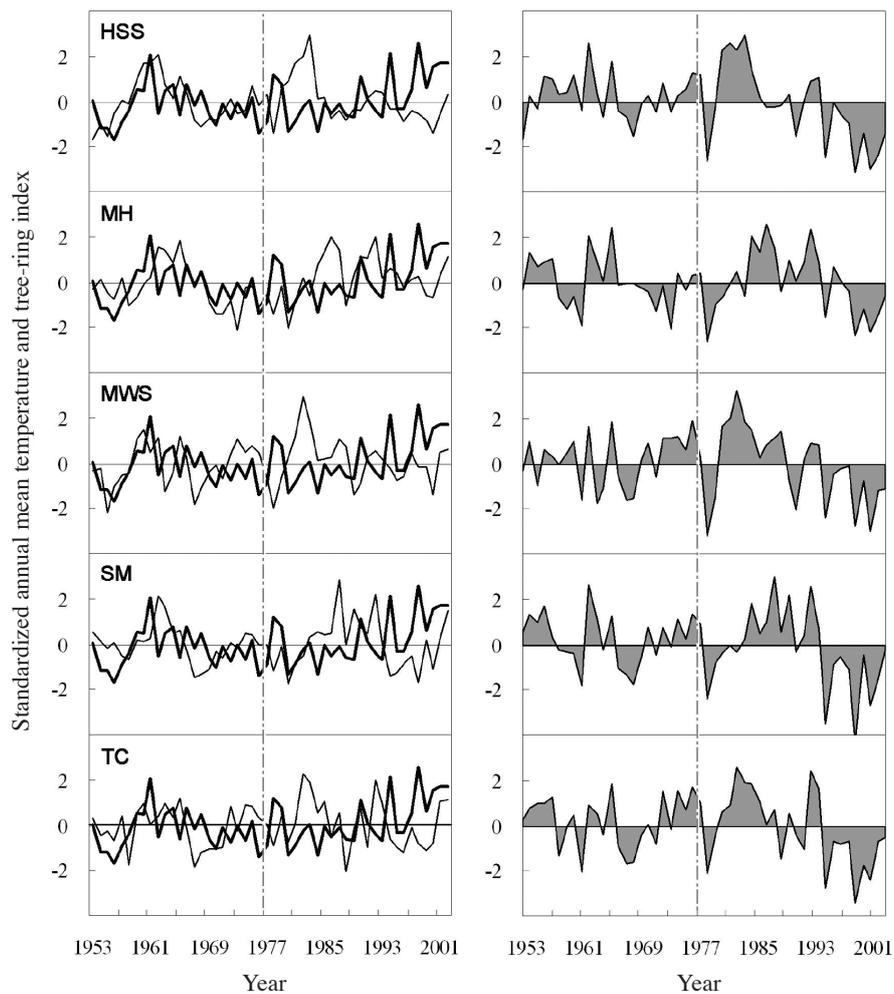


FIGURE 4. Normalized tree-ring chronologies and annual mean temperature at Tunxi (thick line) over the period 1953-2002 (left column), together with their difference (right column)

TABLE 4. Sample linear correlations between tree-ring chronologies and mean temperature at Tunxi during two 25-year periods before and after the 1976-77 climatic shift (* = $p < 0.05$)

Period	1953-1977					1978-2002				
	HSS	MH	MWS	SM	TC	HSS	MH	MWS	SM	TC
Temperature										
Annual	0.45*	0.31	0.24	0.10	0.15	-0.35	0.07	-0.28	-0.20	-0.05
Spring	0.20	0.05	-0.09	-0.05	0.04	-0.08	0.17	0.02	-0.16	0.18
Summer	0.13	-0.10	-0.17	-0.15	-0.33	-0.25	-0.12	-0.40*	-0.32	-0.30
Autumn	0.29	0.50*	0.12	0.22	0.24	-0.22	-0.09	-0.07	-0.24	-0.04
Winter	0.18	0.05	0.57*	0.15	0.32	-0.24	0.15	-0.19	0.15	0.02

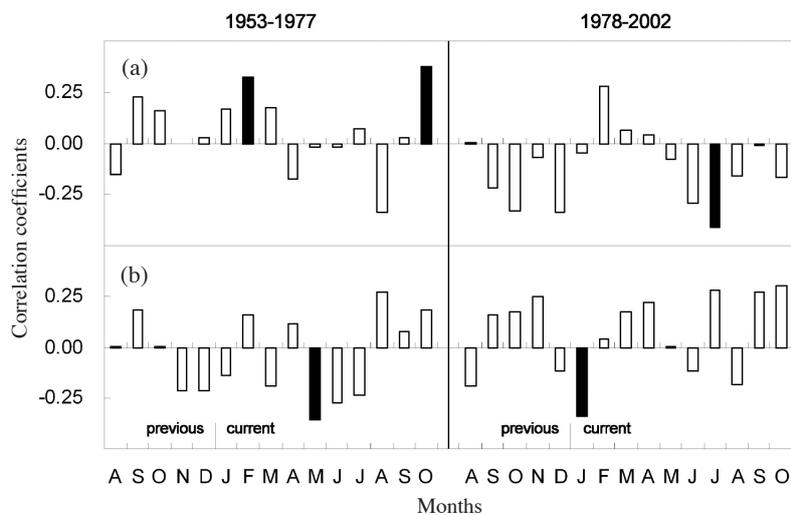


FIGURE 5. Correlation functions between the first principal component of the five tree-ring chronologies and (a) monthly average temperature and (b) total precipitation from the previous August to the current October for the period 1953-1977 and 1978-2002. Black bars represent $p < 0.05$ as tested by bootstrap method

(ENSO) and in the North Pacific (PDO) showed higher values over the more recent decades (Figure 6). PC1 was positively correlated with April to September Niño 3.4 and with July to December PDO over 1978-2002, while there were no significant correlations for the period 1953-1977.

Synoptic analysis between indices of the northern (PDO) and equatorial (Niño 3.4) Pacific SST and gridded surface air temperature showed different patterns before and after 1976/77 over the Asian monsoon region (Figures 7 & 8). For the period 1953-1977, the winter (DJF) Niño 3.4 anomalies were negatively correlated with summer (JJA) surface air temperature anomalies in the east and southeast China sea, whereas the winter PDO anomalies had positive correlations in the south Chinese mainland and southeast China sea. For the period 1978-2002, the winter Niño 3.4 anomalies had strong positive correlations in the north Indian Ocean and southwest Chinese mainland, but there was no correlation over this region with winter PDO anomalies.

Correlation maps of the PC1 scores and mean annual surface temperature showed decreased sensitivity of tree growth to temperature in southeast China after the 1976/77 regime shift in Pacific climate (Figure 9). The PC1 of the

chronologies, while indicating a strong temperature signal in the southeast Chinese mainland (especially around the sampled area) over the period 1953-1977, did not exhibit any correlation with surface temperature over the period 1978-2002.

DISCUSSION

The five subtropical ring-width chronologies from different sites in the Gutian Mountain of southeast China showed statistical characteristics suitable for analyzing the response of tree growth to environmental variations. *P. taiwanensis* and *C. lanceolata* had better dendroclimatic potentials than the other species. *C. eyrei* showed lower sensitivity to climate, which may result from the low number of successfully dated-cores (Table 1) (Holmes 1983). The good correlation between *P. taiwanensis* and *P. massoniana* chronologies may be related to similar responses to climate, possibly favored by taxonomic proximity. Low correlations between these two pine species and *C. lanceolata* may be due to altitudinal differences (Figure 1; Table 1).

Divergence was uncovered between growth indices of these five subtropical tree species and annual mean

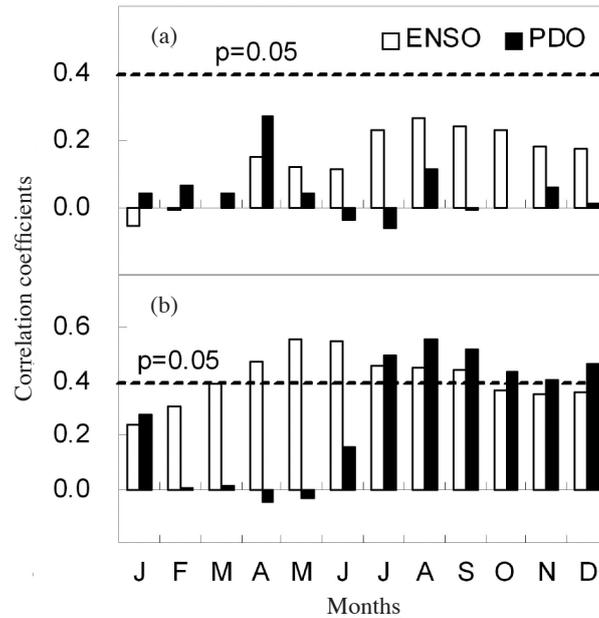


FIGURE 6. Sample linear correlation between the first principal component of the five tree-ring chronologies and monthly indices of mean sea surface temperature in the Niño 3.4 region (ENSO) and North Pacific (PDO) over the periods (a) 1953-1977 and (b) 1978-2002

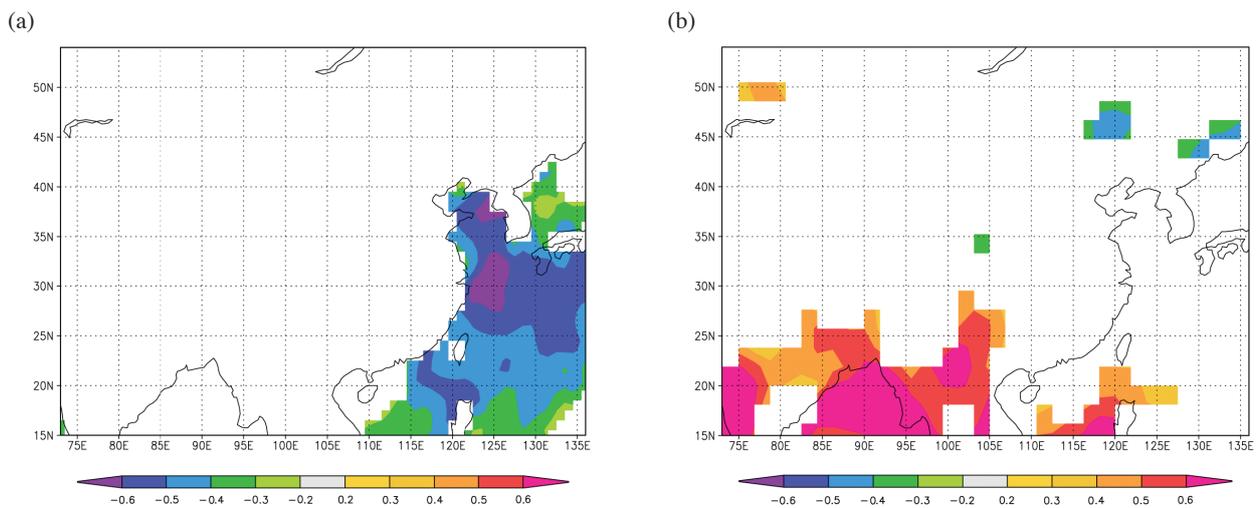


FIGURE 7. Correlation maps between winter (December-February) Niño 3.4 anomalies and following summer (June-August) surface air temperature anomalies for (a) 1953-1977 and (b) 1978-2002. Only correlations with $p < 0.1$ were shown

temperature since the mid-1970s (Figure 4). The relationship between tree growth and temperature switched before and after 1977 (Figure 5), from mostly positive during 1953-1977 to mostly negative or near-zero during 1978-2002. Our results point to a temporal instability in growth-climate response, as found by other authors (Wilson & Elling 2004; Wilson & Topham 2004), especially with regard to recent relationships between tree growth and temperature (Case & Peterson 2007; D'Arrigo et al. 2005; Davi et al. 2003; Lloyd & Fastie 2002; Wilmking et al. 2004). It is possible that under the influence of a relatively cool and wet climate before 1977,

radial growth of the subtropical trees was linked to air temperature, but with the shift to a warmer climate after 1977, tree growth rates generally decreased and became less sensitive to temperature.

Differences between tree growth and annual mean temperature mainly occurred over two periods (1980-1989 and 1994-2002) since 1977 (Figure 4). This was roughly consistent with the two major warm ENSO events in 1982/83 and 1997/98. Climatic conditions in the tropical Pacific can affect the strength and geographical extent of the East Asian and Indian monsoons (Charles et al. 1997; Kinter III et al. 2002; Krishnamurthy & Goswami 2000;

Pillai & Mohankumar 2009; Wang et al. 2001), thereby influencing precipitation and temperature patterns on terrestrial Asia. Correlations between the ENSO index and surface temperature in the Indian Ocean and East China Sea reversed before and after 1977 (Figure 7). This provided evidence that the tropical Pacific is linked differently to the two branches of the Asian summer monsoon, i.e. the East Asian Monsoon (EAM) and the Indian Ocean Monsoon (ISM) (Hong et al. 2006). Recent studies have revealed that these two Asian summer monsoons have an inverse-phase relationship (Sun & Yin 1999; Zhang 2001). During the period 1953–1977, intense convection was focused in the tropical Western Pacific and the EAM was relatively strong compared to the ISM. After 1977, the zone of greater convection moved to the central-east tropical Pacific and the intensity of the two monsoons was reversed, i.e. the EAM was relatively weak compared to the ISM (Hong et al. 2006). Singhrattana et al. (2005a, 2005b) showed changes in correlation between rainfall over central Thailand and ENSO after the late 1970s. Kumar et al. (1999) reported the opposite situation in India, with Indian summer monsoon rainfall significantly correlated with ENSO for the early half of the 20th Century, followed by a loss of correlation in the post-1980s period.

Correlations between ocean indices such as PDO and ENSO with surface air temperatures over the seas surrounding monsoonal China were different before and after 1977 (Figures 6 & 7), suggesting that the reduced sensitivity of tree growth to temperature may be teleconnected to Pacific climate reversals. The PDO index showed a positive correlation before 1977 with surface temperature in the Indian Ocean and East China Sea, but no connection after this time (Figure 8), hinting that a Pacific climate shift could decrease the strengths of both branches of the Asian monsoon. Several other studies have proposed such linkage (Kinter III et al. 2002; Krishnamurthy & Goswami 2000; Wang et al. 2001; Wu 2005). In recent decades, the connection between the Asian monsoon and ENSO has been linked to the atmospheric circulation and oceanic temperatures over the entire North Pacific Ocean (Kinter III et al. 2002). Tropical-extra tropical climate links have been illustrated by D'Arrigo et al. (2005) and Deser et al. (2004). Daniels and Veblen (2004) suggested that the 1976/77 regime shift influenced key aspects of *Nothofagus pumilio* radial growth and seedling establishments at the alpine treeline. A changing influence of ENSO and PDO on tree growth before and after the 1976/77 regime shift in Pacific climate (Figure 6) could therefore be due either to altered effects of local climatic factors on tree growth or to a different relationship between local and large-scale climate. Buckley et al. (2005) also found a temperature-precipitation regime shift related to ENSO in southern Asia pine ring-width chronologies and suggested that further expansion of the tree-ring network across a broader region of Southeast Asia might shed light on the shifting centers of influence of ENSO and the timing of any such shifts.

The altered correlation between PC1 scores and surface temperature over southeast China before and after 1977 (Figure 9) resembles results of Anchukaitis et al. (2006),

who suggested an increasing sensitivity after 1977 of year-to-year tree growth variability to summer precipitation in the southeastern USA (the Appalachian Mountains, northern Georgia and Virginia), possibly driven by the increased sea surface temperatures in the tropical Pacific and Indian Oceans. Given the different relationships between tree growth and temperature before and after the 1976/77 climate shift that we uncovered in subtropical tree species of monsoon-dominated southeastern China, special caution is recommended for temperature reconstructions in this region. Further studies of tree-ring records in temperature-limited environments should take into account potential shifts in climatic variability teleconnected with large-scale atmosphere-ocean interactions.

CONCLUSION

Five subtropical trees in southeast China, *P. taiwanensis*, *S. superba*, *P. massoniana*, *C. lanceolata* and *C. eyrei* are promising species for dendroclimatological studies. They have the similar responses to climate change at large scale. There are significant correlations between five ring-width chronologies and monthly mean temperature of the current year for the period 1953–1977, while which are disappeared over the period 1978–2002. Meanwhile, tree growth and annual mean temperature curves increasingly diverge after around 1977, while they have the relative consistent trend of variations before this time. Two remarkable divergences for the periods 1980–1989 and 1994–2002 between annual mean temperature and ring-width chronologies correspond to two famed ENSO events (El Niño in 1981 and 1998). All of these show that the sensitivity of tree growth to temperature in southeast China decreases significantly. The ENSO and PDO indicate the reversed relationship with tree growth compared to temperature over the periods 1953–1977 and 1978–2002. While a famed climate regime shift occurred around 1976/1977 in the North Pacific and the frequency and intensity of ENSO events has increased over the past several decades, which has influenced climate and bio-systems. These results suggest that the famed 1976/77 regime shift in Pacific climate decreased the sensitivity of tree growth to temperature in Southeast China. In the light of the influence of large-scale climate regime shift on the relationship between local climate and tree growth, we should focus more on treeline advance, forest carbon storage or temperature reconstructions.

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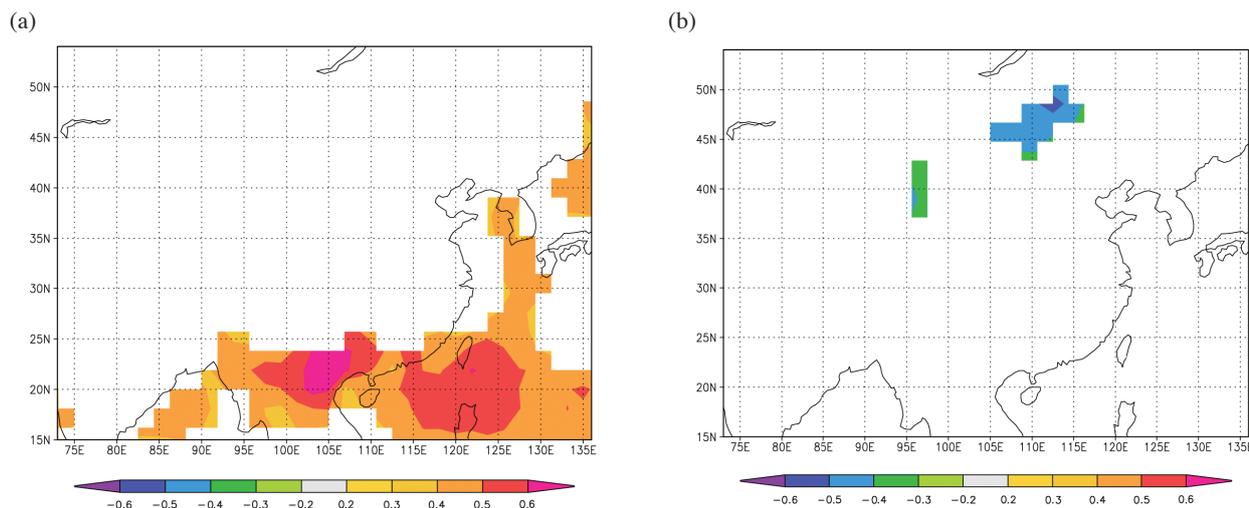


FIGURE 8. Correlation maps between winter (December-February) PDO anomalies and following summer (June to August) surface air temperature anomalies for (a) 1953-1977 and (b) 1978-2002. Only correlations with $p < 0.1$ were shown

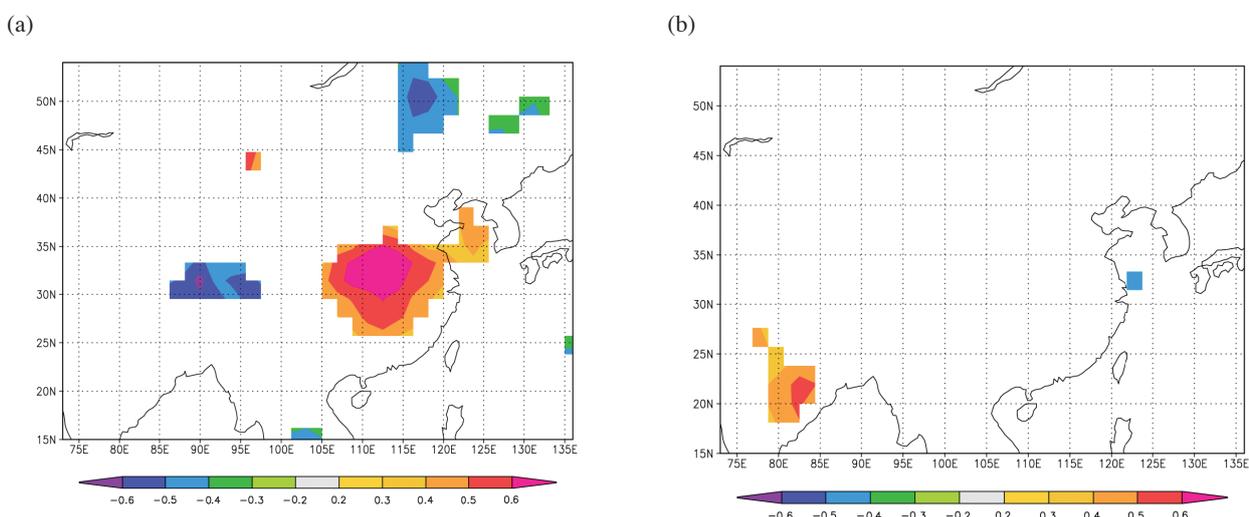


FIGURE 9. Correlation maps between PC1 scores of the five tree-ring chronologies and mean annual surface temperature for (a) 1953-1977 and (b) 1978-2002. Only correlations with $p < 0.1$ were shown

REFERENCES

- Alheit, J., Mollmann, C., Dutz, J., Kornilovs, G., Loewe, P., Mohrholz, V. & Wasmund, N. 2005. Synchronous ecological regime shifts in the central Baltic and the North Sea in the late 1980s. *ICES Journal of Marine Science* 62: 1205-1215.
- Anchukaitis, K.J., Evans, M.N., Kaplan, A., Vaganov, E.A., Hughes, M.K., Grissino-Mayer, H. D. & Cane, M.A. 2006. Forward modeling of regional scale tree-ring patterns in the southeastern United States and the recent influence of summer drought. *Geophysical Research Letters* 33: L04705.
- Andreu, L., Gutierrez, E., Macias, M., Ribas, M., Bosch, O. & Camarero, J.J. 2007. Climate increases regional tree-growth variability in Iberian pine forests. *Global Change Biology* 13: 804-815.
- Barber, V.A., Juday, G.P. & Finney, B.P. 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405: 668-673.
- Biondi, F., Gershunov, A. & Cayan, D.R. 2001. North Pacific decadal climate variability since 1661. *Journal of Climate* 14: 5-10.
- Biondi, F. & Waikul, K. 2004. DENDROCLIM2002: AC++ program for statistical calibration of climate signals in tree-ring chronologies. *Computers & Geosciences* 30: 303-311.
- Biondi, F. & Qeandan, F. 2008. A theory-driven approach to tree-ring standardization: Defining the biological trend from expected basal area increment. *Tree-Ring Research* 64(2): 81-96.
- Bräuning, A. & Mantwill, B. 2004. Increase of Indian summer monsoon rainfall on the Tibetan plateau recorded by tree rings. *Geophysical Research Letters* 31: L24205.
- Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Shiyatov, S.G. & Vaganov, E.A. 1998. Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* 391: 678-682.
- Briffa, K.R., Osborn, T.J. & Schweingruber, F.H. 2004. Large-scale temperature inferences from tree rings: A review. *Global and Planetary Change* 40: 11-26.
- Buckley, B.M., Cook, B.I., Bhattacharyya, A., Dukpa, D. & Chaudhary, V. 2005. Global surface temperature signals in

- pine ring-width chronologies from southern monsoon Asia. *Geophysical Research Letters* 32 (L20704).
- Büntgen, U., Esper, J., Frank, D.C., Nicolussi, K. & Schmidhalter, M. 2005. A 1052-year tree-ring proxy for Alpine summer temperatures. *Climate Dynamics* 25: 141-153.
- Büntgen, U., Frank, D.C., Schmidhalter, M., Neuwirth, B., Seifert, M. & Esper, J. 2006. Growth/climate response shift in a long subalpine spruce chronology. *Trees* 20: 99-110.
- Carrer, M. & Urbinati, C. 2006. Long-term change in the sensitivity of tree-ring growth to climate forcing in *Larix decidua*. *New Phytologist* 170: 861-872.
- Carrer, M., Nola, P., Eduard, J.L., Motta, R. & Urbinati, C. 2007. Regional variability of climate-growth relationships in *Pinus cembra* high elevation forests in the Alps. *Journal of Ecology* 95: 1072-1083.
- Case, M.J. & Peterson, D.L. 2007. Growth-climate relations of Lodgepole pine in the north Cascades National Park, Washington. *Northwest Science* 81(1): 62-75.
- Caso, M., Iez-Abraham, C.G. & Ezcurra, E. 2007. Divergent ecological effects of oceanographic anomalies on terrestrial ecosystems of the Mexican Pacific coast. *Proceedings of the National Academy of Sciences, USA* 104(25): 10530-10535.
- Chang, C.P., Zhang, Y. & Li, T. 2000. Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part I: Roles of the subtropical ridge. *Journal of Climate* 13: 4310-4325.
- Charles, C.D., Hunter, D.E. & Fairbanks, R.G. 1997. Interaction between the ENSO and the Asian Monsoon in a coral record of tropical climate. *Science* 277: 925-928.
- Cook, E.R. & Holmes, R.L. 1986. Users manual for computer program ARSTAN, In *Tree-ring Chronologies of Western North America: California, Eastern Oregon a Northern Great Basin. Chronology Series VI.*, edited by Holmes, R.L., Adams, R. & Fritts, H. Tucson: Arizona University Press. pp. 50-56.
- Daniels, L.D. & Veblen, T.T. 2004. Spatiotemporal influences of climate on altitudinal treeline in northern Patagonia. *Ecology* 85(5): 1284-1296.
- D'Arrigo, R., Villalba, R. & Wiles, G. 2001. Tree-ring estimates of Pacific decadal climate variability. *Climate Dynamics* 18: 219-224.
- D'Arrigo, R., Mashig, E., Frank, D., Wilson, R. & Jacoby, G. 2005. Temperature variability over the past millennium inferred from Northwestern Alaska tree rings. *Climate Dynamics* 24: 227-236.
- D'Arrigo, R., Wilson, R., Deser, C., Wiles, G., Cook, E., Villalba, R., Tudhope, A., Cole, J. & Linsley, B. 2005. Tropical-north Pacific climate linkages over the past four centuries. *Journal of Climate* 18: 5253-5265.
- D'Arrigo, R. & Wilson, R. 2006. On the Asian expression of the PDO. *International Journal of Climatology* 26: 1607-1617.
- D'Arrigo, R., Wilson, R., Liepert, B. & Cherubini, P. 2008. On the 'Divergence Problem' in northern forests: A review of the tree-ring evidence and possible causes. *Global and Planetary Change* 60: 289-305.
- Davi, N.K., Jacoby, G.C. & Wiles, G.C. 2003. Boreal temperature variability inferred from maximum latewood density and tree-ring width data, Wrangell Mountain region, Alaska. *Quaternary Research* 60: 252-262.
- Deser, C., Phillips, A. & Hurrell, J. 2004. Pacific interdecadal climate variability: Linkages between the tropics and North Pacific during boreal winter since 1900. *Journal of Climate* 17: 3109-3124.
- Du, Y., Mi, X., Liu, X., Chen, L. & Ma, K. 2009. Seed dispersal phenology and dispersal syndromes in a subtropical broad-leaved forest of China. *Forest Ecology and Management* 258: 1147-1152.
- Frank, D., Wilson, R. & Esper, J. 2005. Synchronous variability changes in Alpine temperature and tree-ring data over the past two centuries. *Boreas* 34: 498-505.
- Frauenfeld, O.W., Davis, R.E. & Mann, M.E. 2005. A distinctly interdecadal signal of Pacific ocean-atmosphere interaction. *Journal of Climate* 18: 1709-1718.
- Fritts, H.C. 1976. *Tree Rings and Climate*. New York: Academic Press.
- Gong, D.Y. & Ho, C.H. 2002. Shift in the summer rainfall over the Yangtze River valley in the late 1970s. *Geophysical Research Letters* 29: 1436.
- Hoerling, M. & Kumar, A. 2003. The perfect ocean for drought. *Science* 299: 691-694.
- Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43: 69-75.
- Hong, B., Lin, Q. & Hong, Y. 2006. Interconnections between the Asian monsoon, ENSO, and high northern latitude climate during the Holocene. *Chinese Science Bulletin* 51(18): 2169-2177.
- Hu, Z.Z. 1997. Interdecadal variability of summer climate over East Asia and its association with 500 hPa height and global sea surface temperature. *Journal Geophysical Research* 102: 19403-19412.
- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R. & Joseph, D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77: 437-470.
- Kinter III, J.L., Miyakoda, K. & Yang, S. 2002. Recent change in the connection from the Asian monsoon to ENSO. *Journal of Climate* 15: 1203-1215.
- Krishnamurthy, V. & Goswami, B.N. 2000. Indian monsoon-ENSO relationship on interdecadal timescale. *Journal of Climate* 13: 579-595.
- Kumar, K.K., Rajagopalan, B. & Cane, M.A. 1999. On the weakening relationship between Indian monsoon and ENSO. *Science* 284: 2156-2159.
- Legendre, P. & Legendre, L. 1998. *Numerical Ecology*. Amsterdam: Elsevier Science BV.
- Lloyd, A.H. & Fastie, C.L. 2002. Spatial and temporal variability in the growth and climate response of treeline trees in Alaska. *Climatic Change* 52(4): 481-509.
- Lo, T.T. & Hsu, H.H. 2008. The early 1950s regime shift in temperature in Taiwan and East Asia. *Climate Dynamics* 31: 449-461.
- López, B.C., Rodríguez, R., Gracia, C.A. & Sabate, S. 2006. Climatic signals in growth and its relation to ENSO events of two *Prosopis* species following a latitudinal gradient in South America. *Global Change Biology* 12: 897-906.
- Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. & Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78: 1069-1080.
- Miller, A.J., Cayan, D.R., Barnett, T.P., Graham, N.E. & Oberhuber, J.M. 1994. The 1976-77 climate shift of the Pacific ocean. *Oceanography* 7(1): 21-26.
- Oberhuber, W., Kofler, W., Pfeifer, K., Seeber, A., Gruber, A. & Wieser, G. 2008. Long-term changes in tree-ring-climate

- relationships at Mt. Patscherkofel (Tyrol, Austria) since the mid-1980s. *Trees* 22(1): 31-40.
- van Oldenborgh, G.J., Drijfhout, S., van Ulden, A., Haarsma, R., Sterl, A., Severijns, C., Hazeleger, W. & Dijkstra, H. 2009. Western Europe is warming much faster than expected. *Climate of the Past* 5: 1-12.
- Pillai, P.A. & Mohankumar, K. 2009. Effect of late 1970's climate shift on tropospheric biennial oscillation-role of local Indian Ocean processes on Asian summer monsoon. *International Journal of Climatology* 30(4): 509-521.
- Rodionov, S. & Overland, J.E. 2005. Application of a sequential regime shift detection method to the Bering Sea ecosystem. *ICES Journal of Marine Science* 62: 328-332.
- Schöngart, J., Junk, W.J., Piedade, M.T.F., Ayres, J.M., Huttermann, A. & Worbes, M. 2004. Teleconnection between tree growth in the Amazonian floodplains and the El Niño–Southern Oscillation effect. *Global Change Biology* 10: 683-692.
- Singhrratna, N., Rajagopalan, B., Kumar, K.K. & Clark, M. 2005a. Interannual and interdecadal variability of Thailand summer monsoon. *Journal of Climate* 18: 1697-1708.
- Singhrratna, N., Rajagopalan, B., Clark, M. & Kumar, K.K. 2005b. Seasonal forecasting of Thailand summer monsoon rainfall. *International Journal of Climatology* 25: 649-664.
- Sun, S. & Yin, M. 1999. Subtropical high anomalies over the western Pacific and its relations to the Asian monsoon and SST anomaly. *Advances Atmospheric Sciences* 16: 559-568.
- Trenberth, K.E. & Hoar, T.J. 1997. El Nino and climate change. *Geophys. Res. Lett.* 24: 3057-3060.
- Tudhope, A.W., Chilcott, C.P., McCulloch, M.T., Cook, E.R., Chappell, J., Ellam, R.M., Lea, D.W., Lough, J.M. & Shimmield, G.B. 2001. Variability in the El Nino-Southern Oscillation through a glacial-interglacial cycle. *Science* 291(5508): 1511-1517.
- Vaganov, E.A., Hughes, M.K., Kirilyanov, A.V., Schweingruber, F.H. & Silkin, P.P. 1999. Influence of snowfall and melt timing on tree growth in subarctic Eurasia. *Nature* 400: 149-151.
- Villalba, R. 2007. Tree-ring evidence for tropical-extratropical influences on climate variability along the Andes in South America. *PAGES News* 15(2): 23-25.
- Wang, B., Wu, R. & Lau, K.M. 2001. Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the western north Pacific–east Asian monsoons. *Journal of Climate* 14: 4073-4090.
- Wilmking, M., Juday, G.P., Barber, V.A. & Zald, H.S.J. 2004. Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds. *Global Change Biology* 10: 1724-1736.
- Wilson, R., D'Arrigo, R., Buckley, B., Buntgen, U., Esper, J., Frank, D., Luckman, B., Payette, S., Vose, R. & Youngblut, D. 2007. A matter of divergence: Tracking recent warming at hemispheric scales using tree data. *Journal of Geophysical Research* 112: D17103.
- Wilson, R. & Elling, W. 2004. Temporal instability in tree-growth/climate response in the lower Bavarian forest region: Implications for dendroclimatic reconstruction. *Trees* 18: 19-28.
- Wilson, R. & Topham, J. 2004. Violins and climate. *Theoretical and Applied Climatology* 77(1-2): 9-24.
- Wu, B. 2005. Weakening of Indian summer monsoon in recent decades. *Advances Atmospheric Sciences* 22: 21-29.
- Xu, X., Yu, M., Hu, Z., Li, M. & Zhang, F. 2005. Structure and dynamics of *Castanopsis eyrei* population in Gutian Mountain National Nature Reserve in Zhejiang, east China. *Acta Ecologica Sinica* 25(3): 645-653.
- Zhang, R. 2001. Relations of water vapor transport from Indian monsoon with that over East Asia and the summer rainfall in China. *Advances Atmospheric Sciences* 18: 1005-1017.
- Zhang, P., Cheng, H., Edwards, R.L., Chen, F., Wang, Y., Yang, X., Liu, J., Tan, M., Wang, X., Liu, J., An, C., Dai, Z., Zhou, J., Zhang, D., Jia, J., Jin, L. & Johnson, K.R. 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science* 322: 940-942.
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