Forest Ecology and Management 267 (2012) 50–57

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

ENSO and PDO strongly influence Taiwan spruce height growth

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ARTICLE INFO

Article history:
Received 13 September 2011
Received in revised form 12 November 2011
Accepted 17 November 2011
Available online 26 December 2011

Keywords:
Dendrochronology
El Niño-Southern Oscillation
Ensemble empirical mode decomposition
Pacific Decadal Oscillation
Picea morrisonicola
Sea surface temperature

ABSTRACT

To assess the influences of the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) on the mean annual height growth of the Taiwan spruce (*Picea morrisonicola*), we constructed two height growth indices (HGI1 and HGI2) using an ensemble empirical mode decomposition approach based on stem analysis of 19 trees. The most significant periodicities for HGI1 and HGI2 were 4.5 and 15.5 years, respectively. Both indices positively correlated with the mean annual height growth and reflected the influences of local thermal environment variability at various lag times, up to 3 years prior to the shoot extension season. The lagged relationships were likely caused by a combination of the species' two-year height growth process, the delayed responses of the local climate to sea surface temperature (SST) variation, and persistence due to needle lifespan. The correlations between HGI1 and a detrended SST field showed a spatial pattern similar to that of the ENSO. At lags of both 3 and 4 years, the correlations between HGI2 and the SST field revealed a spatial pattern resembling that of PDO. When leading by 3 and 4 years, respectively, the NINO4 and PDO indices positively associated with the mean annual height growth and together explained 37% of the variance; the marginal effect of the NINO4 index was twice as large as that of the PDO index. The results show that the height growth of Taiwan spruce responded to both ENSO and PDO in a positive manner. This study demonstrates that quasi-periodic climate variation on an interannual (ENSO) to interdecadal (PDO) time scale can significantly influence tree growth and should be taken into account when assessing the impact of climate changes on forest productivity, and the results of this study provide a basis for incorporating the influences of such quasi-periodic climate variations into future model-based assessments.

1. Introduction

Climate significantly influences tree growth and forest development. Thus, a major societal concern is how observed and projected climate changes will affect forest ecosystems because the survival of human societies has historically depended strongly on goods and services provided by forests (Boisvenue and Running, 2006; Fischlin et al., 2007).

A significant portion of the observed recent global land warming is caused by ocean warming (Compo and Sardeshmukh, 2009; Swanson et al., 2009). Due to the huge heat capacity of the ocean and the ocean-atmosphere interactions, one signature of ocean temperature variations is the presence of quasi-periodic climate variations (QPCVs). The time scales of QPCVs vary from interannual (e.g., El Niño-Southern Oscillation, ENSO) to interdecadal (e.g., Pacific Decadal Oscillation, PDO) to multidecadal (e.g., Atlantic Multidecadal Oscillation) to centennial or longer (Bindoff et al., 2007).

The effects of the oceanic QPCVs on the land climate are well-documented (e.g., Trenberth et al., 2007), but we only begun to understand how QPCVs affect forest ecosystems during the past decade (e.g., Barichivich et al., 2009; Brienen et al., 2009; Farge et al., 2003; Lo et al., 2010; Peterson and Peterson, 2001; Peterson et al., 2002; Schoennagel et al., 2005). Of the identified QPCVs, those on an interannual to interdecadal time scale are particularly relevant to natural resource management because their periodicities fall within the typical resource management planning time frame.

The Taiwan spruce (*Picea morrisonicola* Hayata), which is endemic to Taiwan, is the southernmost species of the genus. Although the species once had a broader geographic range, it is currently only found at high elevations. The current distribution of the species may reflect past environmental changes, which lead to a population decline. With the island-wide temperature projected to increase between 0.9 and 2.7 °C under a doubled CO_2 scenario (Hsu and Chen, 2002), the species may encounter further reduction in its distribution. Thus, the future of this species is of particular concern because of its biogeographical importance and its current at-risk status (Aljos et al., 1993).

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doi:10.1016/j.foreco.2011.11.028

Due to the difficulties in obtaining accurate annual height growth data, almost all of the established tree growth-climate relationships are based on radial growth. However, height growth is linked more closely to survival and to reproductive potential than radial growth (Gamache and Payette, 2004). Several studies have also suggested that height growth would be more suitable than radial growth for examining the effects of climate variation on tree growth (Jalkanen and Tuovinen, 2001; Pensa et al., 2005). Thus, a complete impact assessment of forest ecosystems must include the potential height growth response to climate change (Bontemps et al., 2009). The main objective of this study is to assess how the annual height growth of the Taiwan spruce responded to ENSO and PDO.

2. Materials and methods

2.1. Study site and species

The study site is located in the Ta-Ta-Chia area of central Taiwan (23°29' N, 120°53′ E, *ca*. 2500–2800 m a.s.l.; Fig. 1), just north of the Tropic of Cancer. The study site is the only region in Taiwan where large areas of natural pure stands of Taiwan spruce can still currently be found.

The nearest weather station at a similar altitude to the study site is the Alishan Weather Station (23°30′ N, 120°48′ E, 2413 m a.s.l.). Between 1954 and 2003, the mean annual temperature at the station was 10.7 °C (5.6 °C in January and 14.2 °C in July, Fig. 2). The mean annual precipitation at the station was approximately 3800 mm, and it is characterized as having a wet summer and dry winter (Fig. 2).

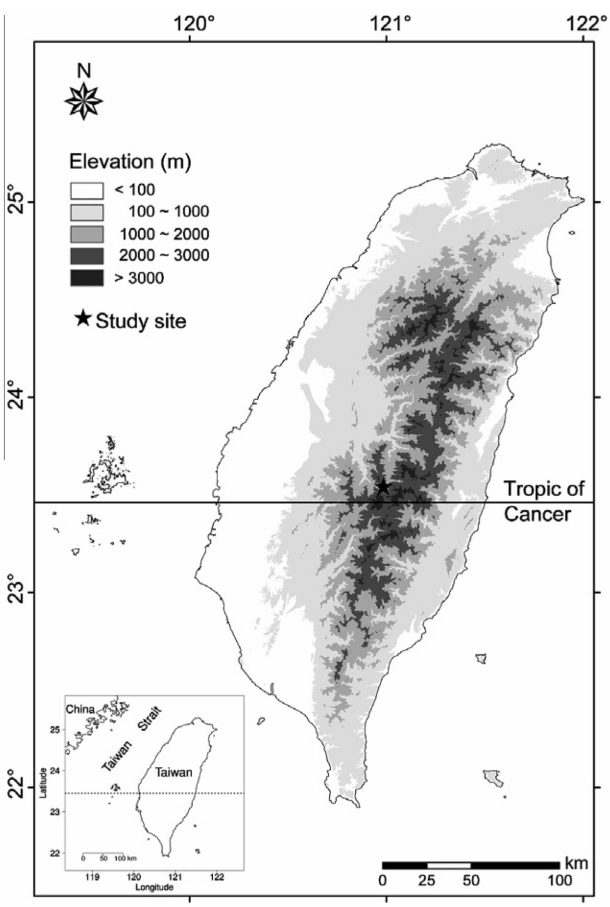

Fig. 1. Location of the study site.

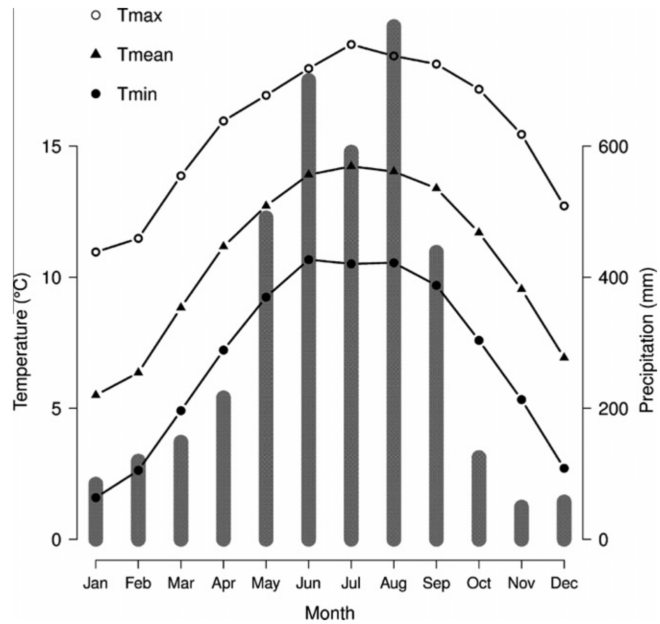

Fig. 2. Summary of the meteorological data from the Alishan Weather Station between 1954 and 2003. T_{min}, T_{mean}, and T_{max} represent the average monthly minimum, mean, and maximum temperatures, respectively. Precip is the average monthly precipitation.

Similar to other spruce species, the Taiwan spruce has only one annual flush. The complete height growth process of the species, from the beginning of terminal bud formation to the end of shoot elongation, is a two-year process (Yong et al., 1998). At the study site, Taiwan spruce terminal buds form during the current growing season and are visible in late August. Main shoot elongation usually begins in mid-May of the following year and completes in mid-June (Yong et al., 1998). Based on field observations and net photosynthesis rate measurements (Weng et al., 2005), height growth processes can be divided into three stages: July to November, December to March, and April to June. The first stage is the bud formation period, and the activities (e.g., differentiation and development of growth units) occurring in that stage affect the height growth during the next year. In the second stage, which is the coldest and the driest period of the year (Fig. 2), bud dormancy is initiated, and the necessary winter chilling is accomplished. In the third growth stage, the terminal buds break their dormancy, and annual height growth both begins and ends (Guan et al., 2009).

2.2. Height growth data

The data used in this study were a subset of the stem analysis data collected in 2004 (Guan et al., 2009). The stem analysis data are comprised of 28 trees from a 3-ha Taiwan spruce plantation established in 1967. From the data set, we selected all trees at least 10 m in height, which included all of the 7 dominant trees and 12 of the 13 codominant trees. The height of the 19 trees ranged from 10.1 to 17.0 m, with an average of 12.9 m, and their dbh ranged from 20.4 to 30.7 cm, with an average of 25.1 cm. Among the selected trees, the earliest recovered hidden growth tip (*nodal septum*) was formed in 1970 (one tree), while the latest tip was formed in 2003 (two trees). We, therefore, only included height growth data between 1971 and 2002 for subsequent data analysis. For the selected trees, the mean annual height growth ranged from 33.8 to 56.7 cm. The mean sensitivity of each growth series ranged from 0.24 to 0.59 with a median value of 0.36, and the mean inter-series correlation was 0.52.

2.3. Data analysis

2.3.1. Construction of height growth indices

We used an ensemble empirical mode decomposition (EEMD) approach (Wu and Huang, 2009) to create two height growth indices, which were subsequently correlated with climate variability.

The EEMD method is an improvement of the empirical mode decomposition (EMD, Huang et al., 1998) method, which is an empirical, but highly efficient and adaptive, method for processing non-linear and non-stationary signals. The main idea of the EMD is to decompose signals into a finite number of intrinsic mode functions (IMFs), which are filtered out from high to low frequency via a spline-based iterative sifting process. Ideally, the decomposition stops when the residue becomes either monotonic or contains only one extremum. In practice, a pre-defined number of IMFs are extracted to avoid over-extraction. Huang and Wu (2008) provided a concise review of the EMD method.

Wu and Huang (2009) developed the EEMD approach to alleviate the signal intermittence problem in the original EMD method. The EEMD method is a Monte Carlo EMD approach in which white noise is added during the decomposition process to achieve better signal separations. For a given dataset, the process repeats a pre-defined number of times, with a different set of white noise each time. An EEMD IMF is the ensemble mean of the corresponding EMD IMFs.

A major advantage of using the EMD-EEMD approach in relating tree growth to climate variability is that there is no need to impose a subjectively selected trend to remove the intrinsic growth trend, which is the first step in the traditional dendrochronological approach (Cook, 1987). Such an advantage is particularly relevant in this study because our time series is relatively short. Removing a growth trend with a short span may filter out the climate signals of interest, whereas a long-span trend would not serve the detrending purpose. The second advantage of using the EMD-EEMD approach is that the decomposition process is additive, and the resulting IMFs would have the same unit of measure as the input series. Finally, the separation of signals with significantly different frequencies will also enable us to better assess the influences of QPCVs of different periodicities.

We decomposed the mean annual height growth series with an ensemble size of 1,000. Each white noise was randomly generated from a normal distribution with a zero mean and a standard deviation of 0.01 of that of the input series. Four IMFs and a residual term were extracted. We created two height growth indices (HGIs), with HGI1 being the first IMF and HGI2 being the sum of the second and third IMFs. The fourth IMF and the residual term represented the trend component in the data. HGI1 (Fig. 3a) contained oscillations with periodicities between 2 and 5 years, with the most significant periodicity at 4.5 years. The periodicities in HGI2 ranged from 6 to 31 years, with the most significant periodicity at about 15.5 years (Fig. 3b). The correlation between HGI1 and HGI2 was not significant (Pearson's $r = 0.12$, $P > 0.5$). However, both indices significantly correlated with the mean annual height growth ($r = 0.76$ for both indices, $P < 0.001$).

2.3.2. Correlations with climate variability

We first established the links between HGIs and the local climate based on data from the Alishan Weather Station. The climate variable examined was the monthly growing-degree-day (GDD, >5 °C) derived from the daily records. Guan et al. (2009) have demonstrated the importance of GDD on the height growth of Taiwan spruce. The correlations between July to June GDD of different temporal resolutions and HGIs were examined at various time lags, with the climate variables leading. HGI1 was prewhitened before applying the correlation function. For each HGI, only the highest correlation was retained.

To identify the responses of annual height growth to the ENSO and the PDO, we used cross-correlation to correlate HGIs with the annually averaged NINO4 (5° N–5° S, 160° E–150° W, Climate Prediction Center, NOAA, http://www.cpc.noaa.gov/data/indices) and PDO (http://jisao.washington.edu/pdo) anomaly indices. Guided by the results, we then correlated the HGIs with the detrended HadISST1 dataset (Rayner et al., 2003), which is a reconstructed 1° × 1° sea surface temperature (SST) field. Finally, we linked the GDD of the identified months to the monthly NINO4 and PDO values between 1967 and 2002 by finding the periods with the most significant correlations, up to a one-year lag with the indices leading.

2.3.3. Evaluating the influences of NINO4 and PDO on height growth

We started by identifying the lags that would yield the highest cross-correlations between the mean annual height growth and the annually averaged NINO4 and PDO anomaly indices with the indices leading. We then used a linear regression approach to

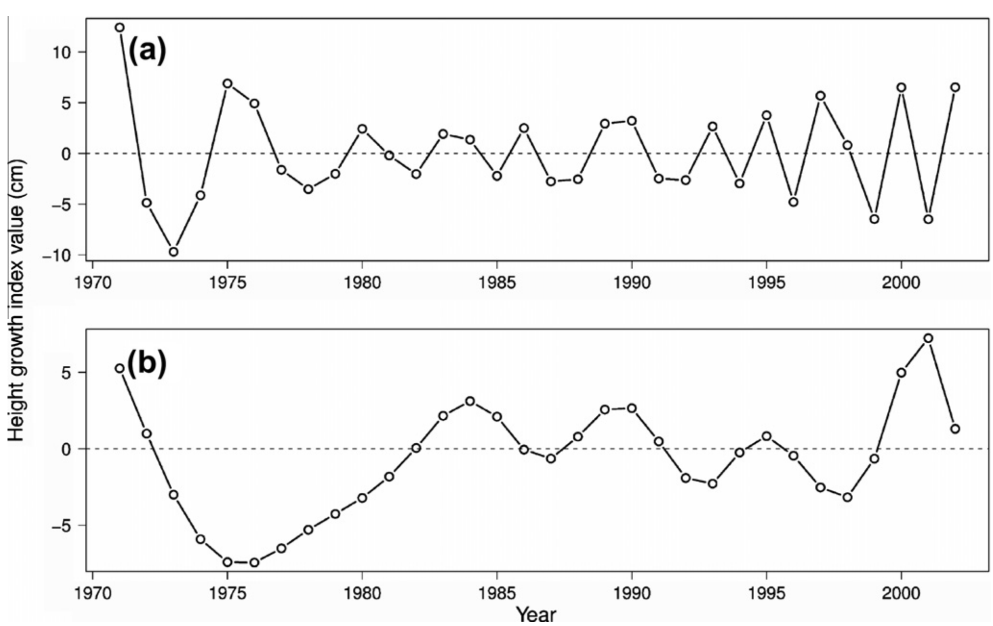

Fig. 3. Time series plots of (a) the first height growth index and (b) the second height growth index.

estimate the marginal effects of the annual NINO4 and PDO anomaly indices on mean annual height growth with appropriate leads in the independent variables.

All data analyses were conducted using R software (R Development Core Team, 2011). For the EEMD decomposition, we ported the MATLAB codes (available at http://rcada.ncu.edu.tw/research1_clip_program.htm) to R. We performed the correlations between each HGI and the gridded SST field via the Royal Netherlands Meteorological Institute Climate Explorer website (http://climexp.knmi.nl).

3. Results

3.1. Correlations between growth indices and the local climate

Because the two HGIs represented height growth signals of different frequencies, they reflected the influences of both local climate and endogenous (e.g., reproductive) processes at different temporal scales. The highest correlation between HGI1 and GDD reflected the influences of previous summer thermal environment. A higher GDD of previous July to September had a positive effect on current year's growth ($r = 0.48$, $P < 0.01$). HGI2 also recorded the influences of summer temperature, but at a longer lag. A warmer August and September of 3 years ago tended to promote the current year's height growth ($r = 0.54$, $P < 0.01$).

3.2. Correlations between HGIs and the NINO4 and PDO indices

The highest cross-correlation between HGI1 and the NINO4 index was found at a lag of 3 years, with the oceanic index leading (Fig. 4a). The correlations between HGI1 and the averaged August$_{t-3}$ to May$_{t-2}$ SST field showed a pattern typical of ENSO (Fig. 5a). HGI1 positively correlated with the NINO4 region SST but negatively correlated with the SSTs in a wedge-shaped pattern that extended from the North Pacific Subtropical Convergence Zone southwest through the Philippine Sea and southeast to New Zealand.

HGI2 had positive and persistent correlations with the PDO at lags of both 3 and 4 years (Fig. 4b). Correlations with the averaged January to November detrended SST field showed a particularly strong pattern consistent with the PDO at both lags (Fig. 5b and c). HGI2 negatively correlated with SSTs in the center of the North Pacific Gyre and in parts of the West Pacific Warm Pool regions, but it positively correlated with the west coast of North America. Of particular interest was the presence of positive correlations around the NINO4 region and strong negative correlations with the SST north and northeast of Taiwan at a four-year lag (Fig. 5c).

3.3. Correlations between the local climate and the NINO4 and PDO indices

The correlations between the NINO4 index and the local climate suggested that a higher averaged previous September to December SST in the NINO4 region tended to be associated with a higher next July to September GDD during the 1967–2002 period ($r = 0.61$, $P < 0.001$; Fig. 6a). If the average PDO value is positive during the boreal winter, then locally next August to September also tended to be warmer ($r = 0.64$, $P < 0.001$; Fig. 6b). However, the SST near Taiwan was negatively associated with the GDD of the same period in both cases.

3.4. Influences of NINO4 and PDO on height growth

The cross-correlation results suggested that the strongest relationship between the mean annual height growth and the two oceanic indices occurred at a three-year lag for NINO4 and at a four-year lag for the PDO. The fitted regression model showed that the two indices together explained approximately 37% of the variance. The estimated coefficients for the annual NINO4 and PDO indices were 6.67 ± 1.93 (mean ± se, $P < 0.01$) and 3.37 ± 1.36 ($P = 0.02$), respectively. The fitted model met all of the regular regression assumptions. Thus, both indices appeared to have had a positive influence on the mean annual height growth, with the marginal effect of the NINO4 index being about twice of that of the PDO index.

4. Discussion

4.1. Linking mean annual height growth to ENSO and PDO

Our results showed that both ENSO and PDO strongly and positively influenced the height growth of Taiwan spruce (Fig. 5), likely

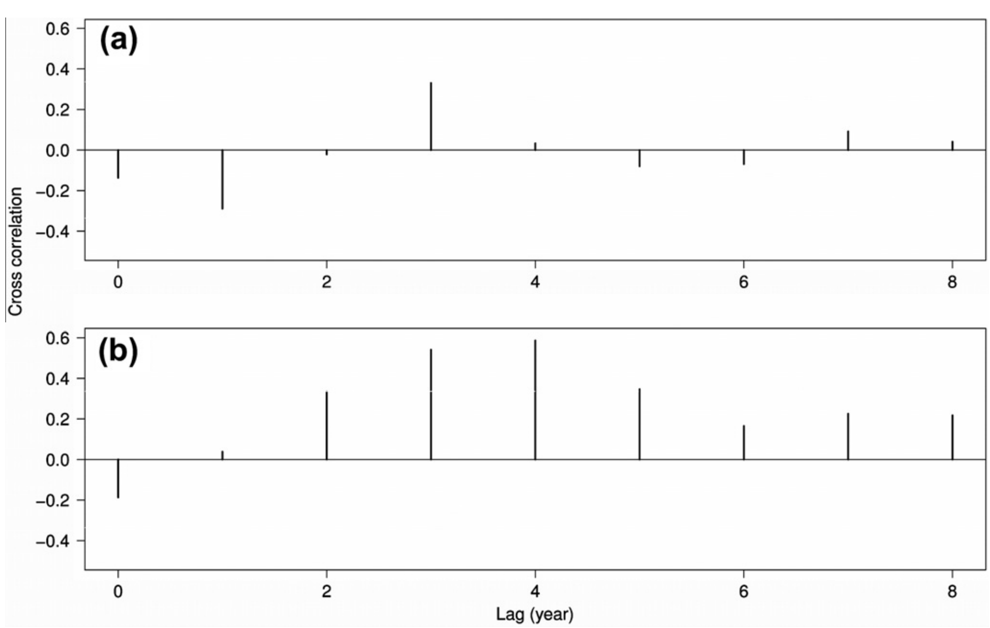

Fig. 4. The cross-correlation between (a) the first height growth index and the NINO4 index and (b) the second height growth index and the PDO index.

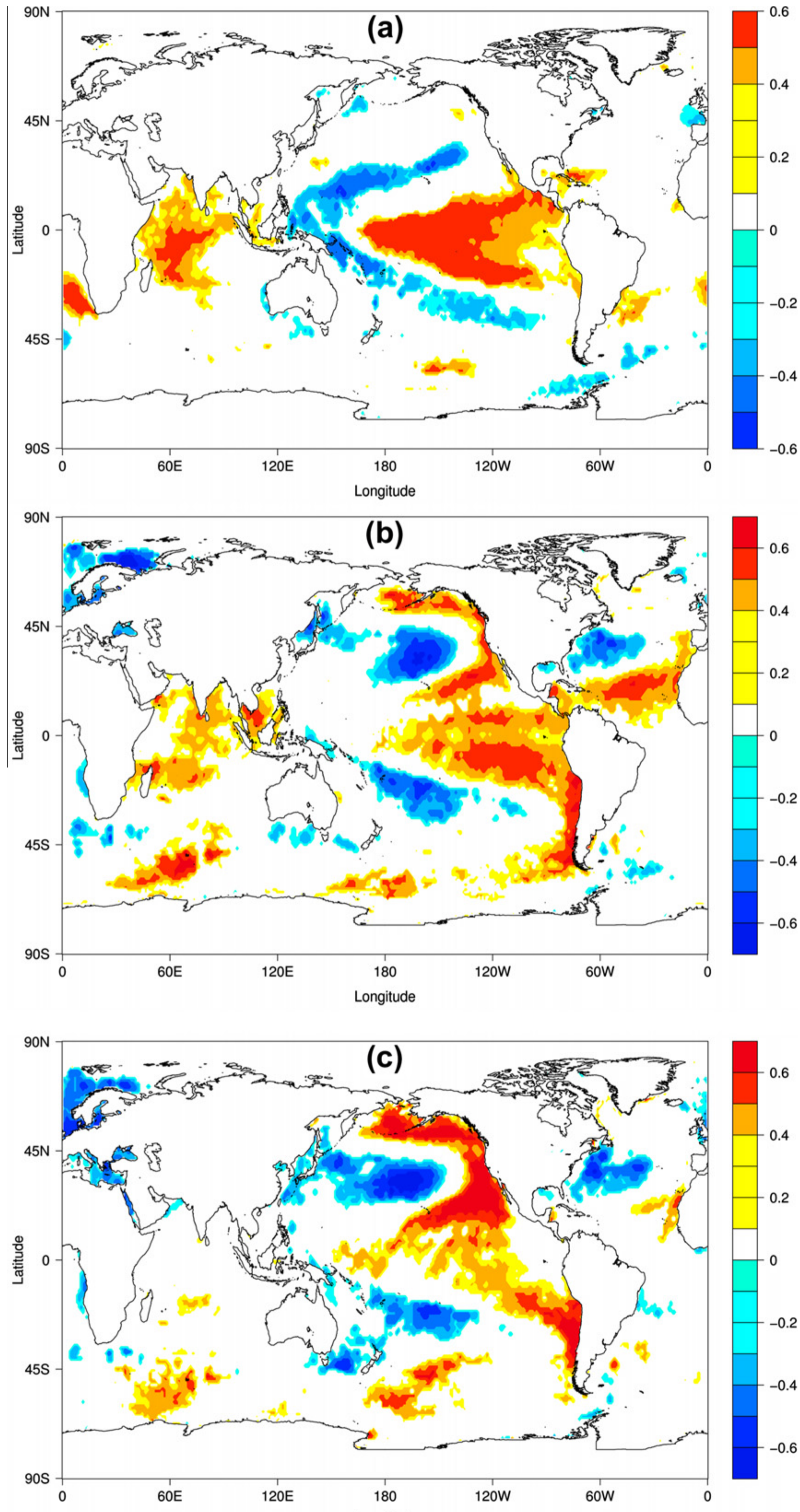

Fig. 5. Correlations between the two height growth indices (HGIs) and the detrended HadISST1 sea surface temperature (SST) field. (a) HGI1 and the averaged August$_{t-2}$ to May$_{t-1}$ SST, (b) HGI2 and the averaged January$_{t-3}$ to November$_{t-3}$ SST, and (c) HGI2 and the averaged January$_{t-4}$ to November$_{t-4}$ SST. Only correlations with $P < 0.1$ are shown.

by modulating the local thermal environment during the early part of the first height growth stage (Fig. 6). For many conifers, mid to late summer period, especially July, is the most important period for height growth (Jalkanen and Tuovinen, 2001; Pensa et al., 2005; Salminen and Jalkanen, 2007), and Taiwan spruce likely responds the same (Guan et al., 2009). Research has suggested that annual height growth may be affected by local climate both directly through an influence on terminal bud formation and elongation and indi-

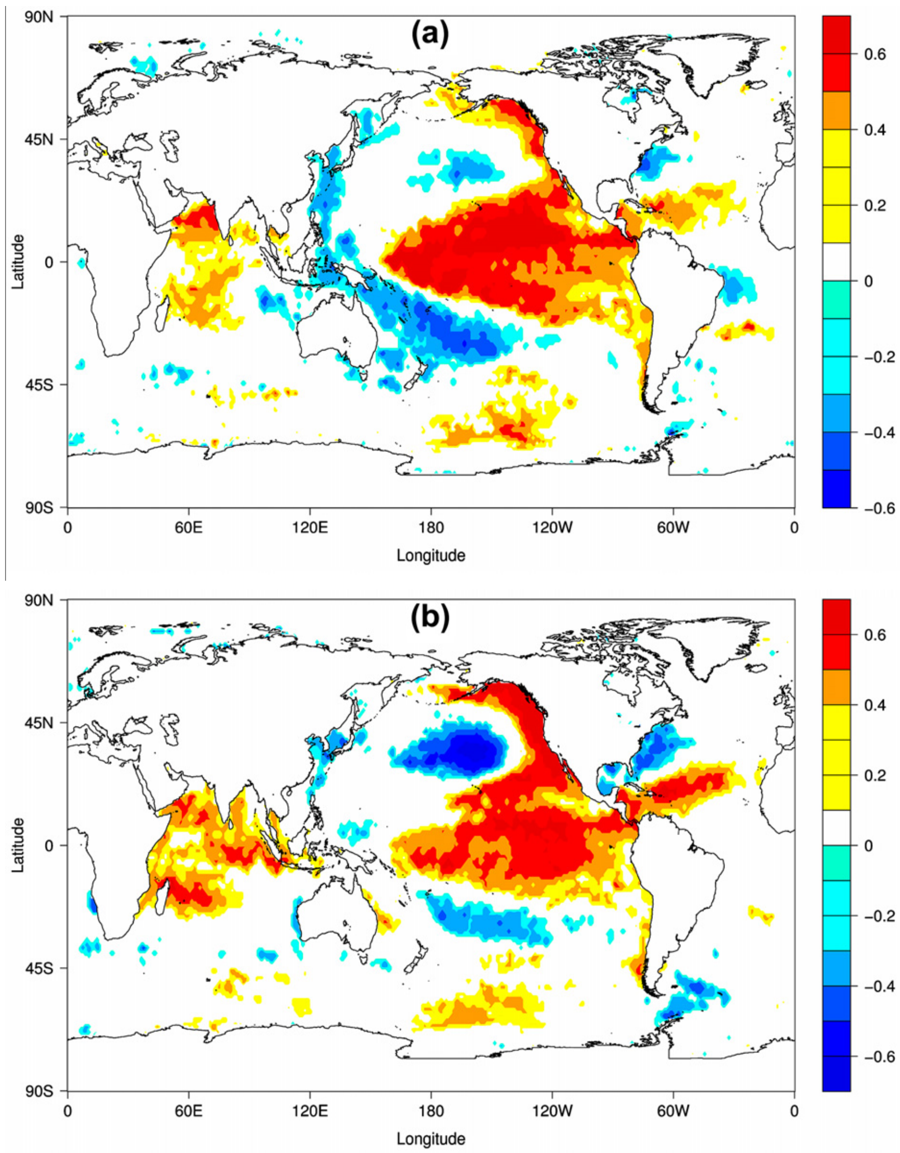

Fig. 6. Correlations between the Alishan Weather Station growing-degree-days (GDD) and the detrended HadISST1 sea surface temperature (SST) field during the 1967–2002 period. (a) Averaged July to September GDD and the averaged previous September to December SST, and (b) Averaged August to September GDD and the averaged previous December to current February SST. Only correlations with $P < 0.1$ are shown.

rectly by changing carbohydrate accumulation and partitioning (Junttila, 1986). As terminal buds are major carbon sink, the positive correlations between HGIs and the local July to September GDD suggest that a warmer environment during that period might allow trees to accumulate more carbohydrate for buds to develop more leader shoot growth units (Salminen and Jalkanen, 2007), which leads to a longer shoot growth next year (Kozlowski et al., 1973).

This study showed that the SST variations around the equatorial Pacific region have positive effects on the height growth of Taiwan spruce (Fig. 5a). As ENSO events tend to reach their mature phases toward the end of the calendar year period (Wang and Fiedler, 2006), thus it likely takes at least another eight months for a mature ENSO event to have a significant effect on the local thermal environment.

As an ENSO-like but long-lived QPCV, it is generally recognized that one oscillatory mode of the PDO has a periodicity of approximately 15–25 years (Minobe, 1999), and the most significant periodicity of HGI2 falls within the range. During the study period, the PDO shifted from the ''cool phase'' mode (negative PDO index values) to the ''warm phase'' mode (positive PDO index values) around 1976–1977, which is considered to be one of the most significant climate regime shifts in the instrumental period. Mantua and Hare (2002) showed that when correlated with the November to April PDO index, the November to April climate of the western Pacific region generally tends to be drier and cooler than normal during the warm phase PDO period. Although during the July to September period, the average SST around Taiwan agreed with the cooler conditions (Fig. 6), but the local thermal environment did not. Thus, the strong positive correlations between HGI2 and the PDO index could be attributed to a warmer environment during the early part of the first height growth stage when the PDO was in a warm phase.

Although HGI2 did not significantly correlate with HGI1, and its most significant periodicity is longer than that of typical ENSO events, its correlation with the SST field around the NINO4 region were still relatively strong, particularly at a four-year lag (Fig. 5c). The correlation between HGI2 and the average January to November NINO4 index value at that lag was 0.46 ($P = 0.01$). We postulate that the positive correlation between HGI2 and the NINO4 index at that lag might be related to the El Niño Modoki, an El Niño-like QPCV that covaries positively with SST variation in the NINO4 region, but with a strong 12-year periodicity (Ashok et al., 2007). The spectrum of HGI2 did contain a peak representing a periodicity around 11 years, although it was statistically not significant.

Both HGI1 and HGI2 recorded the influences of climate variability from 3 to 4 years ago on height growth. The lagged responses of the HGIs to the NINO4 and PDO indices (Figs. 4 and 5) may be due to a combination of the species two-year height growth process, the delayed responses of local climate to Pacific SST variation (Fig. 6), and the presence of persistence (autocorrelation) in height growth (Fritts, 1976). Our analysis demonstrated that the variation of Pacific SSTs required several months to influence local climate, likely through ocean circulation. It might take several more months for the SST influences to have an apparent effect on height growth because of the two-year height growth process. Thus, it could be at least a 6- to 12-month lag for height growth to reflect SST variation. The persistence in height growth might be caused by the needle lifespan of the Taiwan spruce, which is usually 3 years for plantation trees at the study site. If the climate conditions are favorable for growth during the early period of the first height growth stage, it could lead to the production of more needles next year. Such a feed forward scenario could persist throughout the entire needle lifespan.

4.2. ENSO, PDO, and tree growth

This study shows that it is possible to separate higher and lower frequency climate influences on tree growth using EEMD and that a substantial portion of the variability in the mean annual height growth of the Taiwan spruce was likely due to ENSO and PDO. Several studies have shown that the same QPCVs also significantly influence the tree growth on the eastern part of the Pacific basin (e.g., Barichivich et al., 2009; Brienen et al., 2009; Farge et al., 2003; Lo et al., 2010; Peterson and Peterson, 2001; Peterson et al., 2002; Schoennagel et al., 2005). Our study extends their findings to the western edge of the northern Pacific basin. Furthermore, this study also shows that the marginal effect on the mean annual height growth of the Taiwan spruce was greater for the higher frequency QPCV. As the periodicity of the canonical ENSO is about 2–7 years (McPhaden et al., 2006), it would be expected to influence local climate more frequently than the lower frequency PDO and, thus, should have a stronger effect on height growth. Our study also suggests that a moderately warmer summer under the projected climate change might be beneficial to the height growth of Taiwan spruce.

Although the role of ENSO and PDO on the height growth of the Taiwan spruce at the study site seems clear, we should caution that the separation of higher and lower frequency QPCV influences cannot be assumed to also separate the anthropogenically modified climate from the natural climate variability. When assessing the impact of climate change on forest ecosystems, it is always difficult to separate the influences of natural climate variability and anthropogenic forcing (Boisvenue and Running, 2006). Thus, one critical question remains. Did the QPCVs examined include influences from anthropogenic forcing? Several studies have identified the influences of anthropogenic forcing on ENSO frequency (e.g., Wu et al., 2001) and trends (e.g., Shiogama et al., 2005), but overall, the modeling results regarding the role of the anthropogenic forcing on lower frequency climate features, such as the ENSO and PDO, are still inconclusive (McPhaden et al., 2006). Results from recent studies suggest that it is likely that the effect of anthropogenic forcing on lower frequency climatic components is still small relative to natural forcing and that the lower frequency effects are still predominately due to the natural climate regime (Compo and Sardeshmukh, 2010; Swanson et al., 2009).

Nowadays, some of the existing coupled general circulation models are able to reproduce ENSO- and PDO-like behaviors under different climate warming scenarios (e.g., Lapp et al., 2011; Meehl et al., 2011; Oshima and Tanimoto, 2009). Assuming that the influences of ENSO and PDO on height growth of plantation Taiwan spruce are likely to have been of a similar magnitude in the past and may be projected as such into the near future, the results of this study provide a basis to incorporate the influences of ENSO and PDO into our future model-based assessment. This study clearly demonstrates that it is essential for us to do so, as such QPCVs can significantly affect tree growth. Otherwise, we may introduce bias when assessing the impacts of anthropogenic forcing on forest productivity.

Acknowledgements

This study was supported by the National Science Council of Taiwan (NSC97-2627-M-002-021, NSC97-2621-B-002-002-MY3). We thank Dr. Norden E. Huang for making the MATLAB EEMD codes available and providing valuable comments on the use of EEMD in dendrochronology. We also thank the Central Weather Bureau of Taiwan for providing the meteorological data.

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