



Process based model sheds light on climate sensitivity of Mediterranean tree-ring width

R. Touchan¹, V. V. Shishov², D. M. Meko¹, I. Nouiri³, and A. Grachev²

¹Laboratory of Tree-Ring Research, The University of Arizona, P.O. Box 210058 Tucson, Arizona 85721-0058, USA

²Siberian Federal University, Prospekt Svobodniy 79, Krasnoyarsk, 660041, Russia

³National Institute of Agronomy of Tunisia, 43 Avenue Charles Nicolle, 1002 Tunis, Tunisia

Correspondence to: R. Touchan (rtouchan@ltr.arizona.edu)

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Abstract. We use the process-based VS (Vaganov-Shashkin) model to investigate whether a regional *Pinus halepensis* tree-ring chronology from Tunisia can be simulated as a function of climate alone by employing a biological model linking day length and daily temperature and precipitation (AD 1959–2004) from a climate station to ring-width variations. We check performance of the model on independent data by a validation exercise in which the model's parameters are tuned using data for 1982–2004 and the model is applied to generate tree-ring indices for 1959–1981. The validation exercise yields a highly significant positive correlation between the residual chronology and estimated growth curve ($r = 0.76$ $p < 0.0001$, $n = 23$). The model shows that the average duration of the growing season is 191 days, with considerable variation from year to year. On average, soil moisture limits tree-ring growth for 128 days and temperature for 63 days. Model results depend on chosen values of parameters, in particular a parameter specifying a balance ratio between soil moisture and precipitation. Future work in the Mediterranean region should include multi-year natural experiments to verify patterns of cambial-growth variation suggested by the VS model.

of such events in the future. Long time series of tree-ring growth are one of the best sources of proxy data for reconstructing past records of precipitation, streamflow, and drought on interannual to centennial time scales during the late Holocene. Tree-ring records are annually resolved, well-replicated, and can be calibrated and validated against the instrumental record. Dendroclimatic studies have been performed in several North African countries, including Morocco (e.g. Till and Guiot, 1990; Chbouki et al., 1995; Glueck and Stockton, 2001; Esper et al., 2007; Touchan et al., 2011), Algeria (Messaoudene and Tessier, 1997; Touchan et al., 2008a, 2011), and Tunisia (Aloui and Serre-Bachet, 1987; Tessier et al., 1994; Touchan et al., 2008a, b, 2011).

Generally these dendroclimatic studies assume that annual tree-ring growth is adequately determined by a linear function of local or regional precipitation and temperature with a set of coefficients that are temporally invariant. However, various researchers have stressed that tree-ring records are the result of multivariate, often nonlinear, biological and physical processes (Fritts, 1976; Vaganov et al., 2006; Anchukaitis et al., 2006; Evans et al., 2006). There are non-climatic influences on tree-ring records, including tree biology, size, age and localized forest dynamics (Cook and Kairiukstis, 1990). This represents a problem for both single-variable dendroclimatic reconstructions using linear statistical calibration of the tree-ring proxy data and for prediction of the impacts of climate change on tree biology and forest ecology. Linear empirical–statistical analyses alone cannot be used to demonstrate a physical or biological mechanism for variability or change in the climate–tree growth relationship.

1 Introduction

Instrumental records such as precipitation and temperature can be extended back several centuries with proxy data in North Africa. The resulting records can provide estimates of the past frequency and severity of climatic anomalies and these in turn can be used to help anticipate the probability

The process-based VS (Vaganov-Shashkin) model (Vaganov et al., 2006) can be used to resolve the critical processes linking climate variables to tree-ring formation. This model allows us to identify and account for such processes in developing better estimates of past climate. In this paper, we investigate whether a regional *Pinus halepensis* tree-ring chronology from Tunisia can be simulated as a function of climate alone by employing the VS model to link day length and daily temperature and precipitation from a climate station to ring-width variations (Vaganov et al., 1999, 2006).

2 Methods

We used a tree ring chronology and a modeling approach to evaluate whether the tree ring chronology could be simulated as a function of climate alone. Data used include a regional tree-ring chronology of *Pinus halepensis* from Tunisia (Touchan et al., 2008b) and daily precipitation and temperature (A.D. 1959–2004) for the Jendouba weather station (36.48° N 8.8° E, 140 m a.s.l.). The regional chronology was built from a combination of 84 series of ring-width measurements from four sites in Tunisia. The sites are at a range of elevations from 383 m to 1100 m in the region 35.58° N–36.23° N, 8.43°–9.30° E. These sites and chronologies are described in detail elsewhere (Touchan et al., 2008b).

The process-based VS model used here has two unique characteristics. First, it deals with rates of growth of cells as if their formation in the cambium is influenced entirely by the physical environment. Second, it deals explicitly with the dynamics of cell growth, division, and maturation.

The model computes the integral growth rate Gr and simulates conifer tree-ring formation from three variables: solar radiation, daily surface air temperature, and soil moisture (Vaganov et al., 2006).

The growth rate on a specific day *t* is modeled as

$$Gr(t) = g_I(t) \min\{g_T(t), g_W(t)\},$$

where $g_I(t)$, $g_T(t)$, $g_W(t)$ are partial growth rates depending on light *I*, temperature *T*, and soil moisture *W*

The partial rate $g_I(t)$ is a function of latitude, declination angle, and hour angles (Gates, 1980) (Fig. 1) and can be described as:

$$g_I(t) = I / I_0,$$

where $I = I_0(\cos h_s \sin \varphi \sin \theta + \sin h_s \cos \varphi \cos \theta)$,

$$\cos h_s = \tan \varphi \tan \theta,$$

$$\sin \theta = \sin(23.5\pi / 180) \sin(\pi(t - 80) / 180)$$

φ – latitude (in radians),

t – number of day in the year

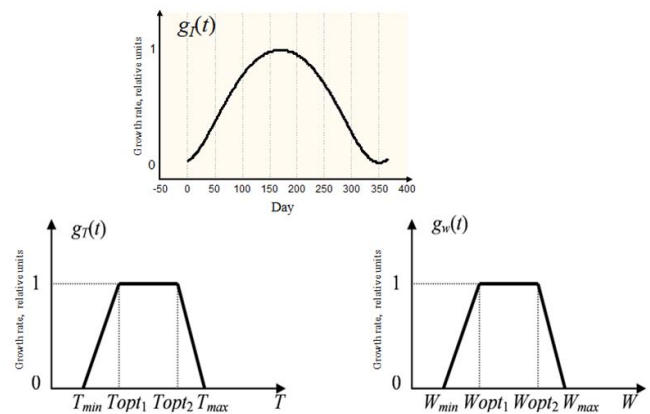


Fig. 1. Harmonic function that defines partial growth rate $g_I(t)$ depending on day length and piece-wise linear functions that define partial growth rates ($g_T(t)$ and $g_W(t)$) depending on temperature *T* and soil moisture *W*.

h_s – hour angle for the latitude

θ – declination angle for the latitude

I_0 – direct solar irradiation for the Earth ($\approx 1360 \text{ W m}^{-2}$)

A water-balance equation is used to determine the water content in the soil from daily mean temperature and precipitation (Thorntwaite and Mather, 1955; Alisov, 1961):

$$\Delta W = f(P) - E - \Lambda W, (W_{\min} \leq W \leq W_{\max})$$

where ΔW – first difference of water content in the soil,
 $f(P)$ – precipitation amount in the soil described by:

$$f(P) = \begin{cases} k_1 P, & \text{if } k_1 P < P_{\max} \\ P_{\max}, & \text{if } k_1 P \geq P_{\max} \end{cases},$$

P – daily precipitation,

E – tree transpiration,

ΛW – water drainage from the soil (Vaganov et al., 2006).

k_1 – fraction of precipitation penetrating soil (not caught by crown) (see Table 1),

P_{\max} – maximum daily precipitation for saturated soil (see Table 1).

The rates $g_T(t)$ and $g_W(t)$ are defined as piece-wise linear functions (Vaganov et al., 2006; Evans et al., 2006; Anchukaitis et al., 2006) (See Fig. 1).

In the paper we used VS model Version 5.0, developed in Fortran by A. V. Shashkin (Vaganov et al., 2006). The VS model is multi-parametric (see Table 1), and a main difficulty is determination of biologically reasonable parameters

Table 1. Optimal model parameters¹ estimated calibration of VS model over period 1982–2004.

Parameter	Description (Units)	Value
T_{\min}	Minimum temperature for tree growth (°C)	8.000
$T_{\text{opt}1}$	Lower end of range of optimal temperatures (°C)	16.00
$T_{\text{opt}2}$	Upper end of range of optimal temperatures (°C)	24.00
T_{\max}	Maximum temperature for tree growth (°C)	28.00
W_{\min}	Minimum soil moisture for tree growth, relative to saturated soil (v/vs)	0.040
$W_{\text{opt}1}$	Lower end of range of optimal soil moistures (v/vs)	0.140
$W_{\text{opt}2}$	Upper end of range of optimal soil moistures (v/vs)	0.220
W_{\max}	Maximum soil moisture for tree growth (v/vs)	0.500
W_0	Initial soil moisture (v/vs)	0.100
W_w	Minimum soil moisture (wilting point)	0.020
T_{beg}	Temperature sum for initiation of growth (°C)	120.0
t_{beg}	Time period for temperature sum (days)	10.00
l_r	Depth of root system (mm)	1500
P_{\max}	Maximum daily precipitation for saturated soil (mm/day)	20.00
k_1	Fraction of precip. penetrating soil (not caught by crown) (rel. unit)	0.720
k_2	First coefficient for calculation of transpiration (mm/day)	0.120
k_3	Second coefficient for calculation of transpiration (mm/day)	0.175
Λ	Coefficient for water drainage from soil (rel. unit)	0.000
t_c	Cambial model time step (days)	0.200
V_{cr}	Minimum cambial cell growth rate (no units)	0.100
D_0	Initial cambial cell size (μm)	4.000
D_{cr}	Cell size at which mitotic cycle begins (μm)	8.000
V_m	Growth rate during mitotic cycle ($\mu\text{m}/\text{day}$)	1.000
D_m	Cambial cell size at which mitosis occurs (μm)	10.00

¹Description of parameters is according to Evans et al. (2006)

that provide a good approximation of the initial, or observed, tree-ring chronology, such that the simulated chronology is highly correlated with the observed chronology.

Appropriate temperature parameters for conifer trees, such as the Aleppo pine chronology used in the model, were selected from published studies of natural (uncontrolled) systems (Deslauriers and Morin, 2005; Rossi et al., 2006, 2007, 2008). Water-use efficiency in dry environments is difficult to specify because conifer trees respond differently from one environment to the other (Oberhuber and Gruber, 2010; Gruber et al., 2010). Therefore, optimal parameters were chosen manually by trial and error using the model and average daily variation of model soil moisture from 1982–2004 (Table 1, Figs. 3, 4). As this process guarantees some agreement of simulated and observed chronology, it is critical to test the performance on independent data. We did this by applying the model and climate data for 1959–1981 to simulate the chronology for that earlier period.

3 Results and discussion

3.1 VS-model calibration and verification

With the estimated optimal parameters (see Table 1) we obtained highly significant positive correlation between the initial chronology and estimated growth curve ($r = 0.76$, $p < 0.0001$, $n = 23$ years) for the calibration period 1982–2004 (Fig. 2). When the model was applied to simulate the chronology for a period (1959–1981) outside the period used to tune the parameters, agreement of observed with simulated chronology was also strong: the high positive correlation ($r = 0.63$, $p < 0.0001$, $n = 23$ years) between curves (Fig. 2) confirms that the VS model can be used to estimate the non-linear tree-growth response to climate changes in the past for specific local drought conditions, as well as to simulate tree growth (particularly cambial activity and cell formation) under extreme environmental changes.

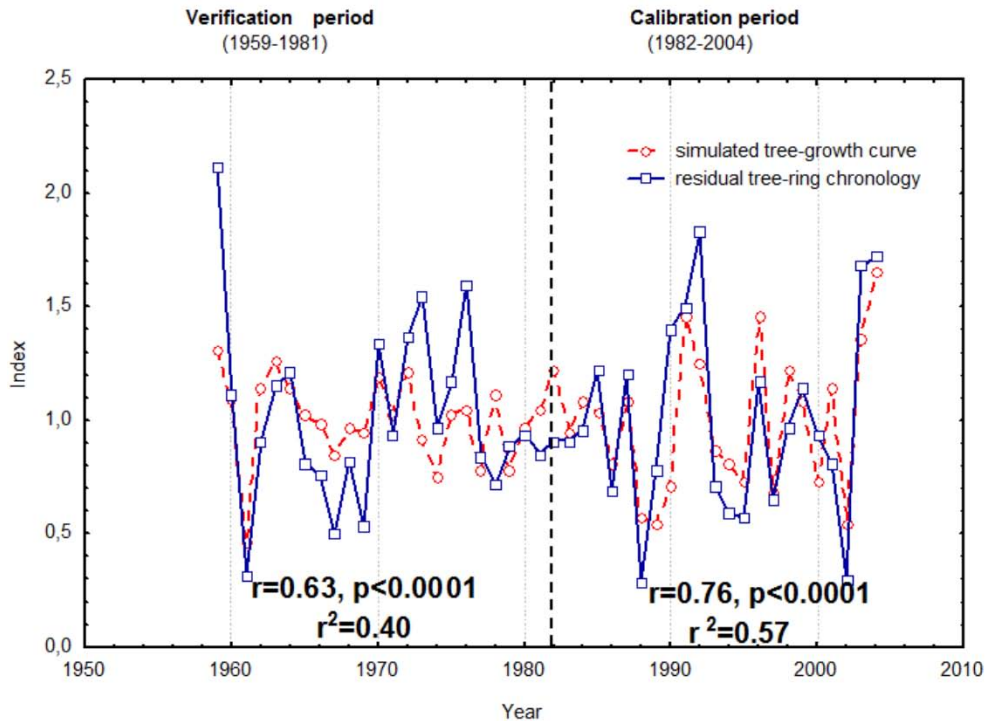


Fig. 2. Variations of initial tree-ring residual chronology (blue solid line) and simulated tree-growth curve (red dashed line) for calibration period (1982–2004) and verification period (1959–1981).

3.2 Analysis of internal model characteristics

The VS model allows us to analyze features of tree-ring growth response in specific environmental conditions. For example, we can estimate the partial influence of temperature and precipitation on tree-ring formation and the water content of the soil at various times throughout the growing season. Moreover, we can trace the process of cell formation in the tree ring under conditions for which we have cell measurements for model verification (Vaganov et al., 2006). The estimated soil moisture in our region is shown by the VS model to increase at the start of each year, reach a maximum in April, and then monotonically decrease till August. We note that these results are consistent with experimental observations for water content of soil in that region (Kleeberg and Koplitz-Weissgerber, 1983).

The limiting influence of climatic variables on tree growth during the growing season is a critical question. Standard multiple regression techniques using monthly climatic data cannot address that question. It is necessary to consider nonlinear influences operating down to at least the daily time step in estimating tree growth by climatic forcing (temperature, precipitation and solar irradiation) (Vaganov et al., 2006).

The VS-model output of partial tree growth rates shows that at the start of each year, growth rate $g_T(t)$ is less than $g_W(t)$, such that tree growth is limited by temperature until April (Fig. 3). From April to August soil moisture is the

limiting factor to tree-ring growth: partial $g_W(t)$ is generally less than partial $g_T(t)$ (Fig. 3).

An integral growth rate $Gr(t)$ lower than the model-specified minimum cambial cell growth rate V_{Cr} indicates no growth. Accordingly, our results suggest that cambial activity stops in the middle of July and does not resume until next year (Fig. 4), despite partial growth rates $g_T(t)$ and $g_W(t)$ (especially, in October, November and December) being favorable for resumption of growth again after August–September (Fig. 4). The reason growth does not resume is day-length (or solar irradiance), which continues decreasing in September. In this case, $g_I(t)$ and its nonlinear interaction with $g_W(t)$ is the common limiting growth factor beginning in late August. Detailed analysis of simulated annual growing seasons shows that in some favorable years (e.g. 1982, 1990, 1994, 2002) trees could possibly change their strategy of growth. They could change their unimodal growth pattern (with one spring-summer period of cambial activity per year) to bimodal – cambial cell division activated again in autumn by extremely favorable soil moisture. The possibility of bimodal growth patterns in Spain was shown by De Luis et al. (2011). A bimodal growth pattern in our region needs to be verified by multi-year natural experiments.

The time plot of average integral growth rate (Fig. 4), and its position relative to the minimum cambial growth rate can be analyzed to compute various growth statistics. For our example, the average duration of the growing season is 191

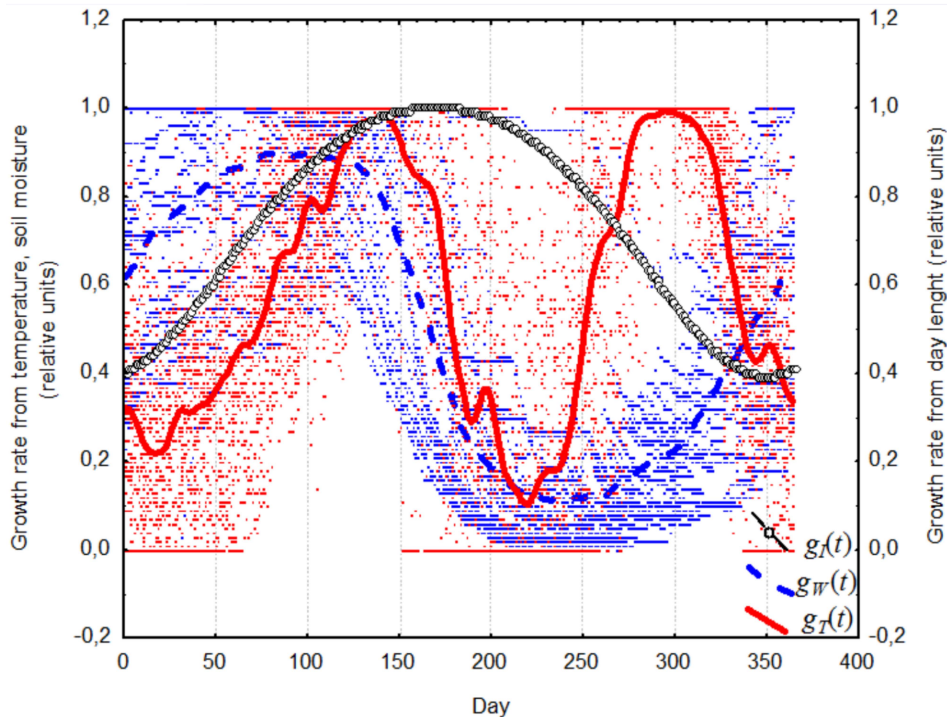


Fig. 3. Partial growth rates depending on day length $g_L(t)$ (black circles), soil moisture $g_W(t)$ (blue line) and temperature $g_T(t)$ (red line) for 1982–2004 fitted by negative exponentially-weighted smoothing (McLain, 1974)². Blue and red dots on the graph are daily values of partial rates superimposed on each other for each year.

² The negative exponentially-weighted fitting (smoothing) procedure is based on a polynomial regression algorithm similar to the one used in distance-weighted least squares. Exponential weighting offers an adequate balance between preventing points at remote subregions from biasing the curve while not ignoring them entirely (McLain 1974). Negative exponentially-weighted fitting is used to identify patterns in developing quantitative models of phenomenon. Specifically, the curve revealed by the smoothing procedure often consists of segments that cannot easily be described by one function (e.g. a particular polynomial function.)

days, with a standard deviation of 82 days. On average, soil moisture limits tree-ring growth for 128 days and temperature for 63 days. Verifying the results from simulations would require direct measurements of cambial growth, including measurements of cell sizes over several growing seasons. Such measurements can improve the model's performance for a given species, and help in the interpretation of features such as false rings, or intra-annual density fluctuations. These features are implied by the bimodal growth curve in Fig. 4. In fact the VS model allows the user to simulate cambial activity during the entire growing season, including the estimation of the number and sizes of new cells in the current tree ring (Vaganov et al., 2006). We note that false rings were observed in some samples from one of the four tree-ring sites contributing to the regional chronology.

The VS model indicates variability in the start of the growing season. The mean start date is the 34th day of year, with a standard deviation of 26 days. The start of the growing season is defined by the rate of cambial cell growth. If the rate of growth is more than 0.1, the growing season is assumed to have started (see Table 1, V_{cr}). The growing season is assumed to end when the integral growth rate $Gr(t)$ falls

below 0.1. Note that this happened in June–July of a recent year. During the 1982–2004 analysis period the principal limiting factor is soil moisture, indicated by the VS model to have limited growth in 67 % of the growing-season days.

3.3 Drought simulation and tree growth response

Tree-growth simulations will depend to some extent on the settings of all parameters. An especially important algorithm of the VS model utilizes a balance ratio between precipitation and soil moisture. Specifically, soil moisture eventually becomes stable with lower precipitation because a direct decrease of precipitation (up to 50 %) involves a decrease of tree transpiration. The sensitivity of soil moisture to precipitation in the VS model can be varied by changing the setting of the drainage coefficient Λ , defined as an additional fraction (portion) of water evaporating from soil and not included in the tree transpiration (Vaganov, 2006). As a sensitivity experiment, we varied Λ from 0.000 to 0.007 (with step 0.001), generated a tree-ring chronology with each setting, and observed the change in chronology statistics. Each step increase in drainage coefficient over this range

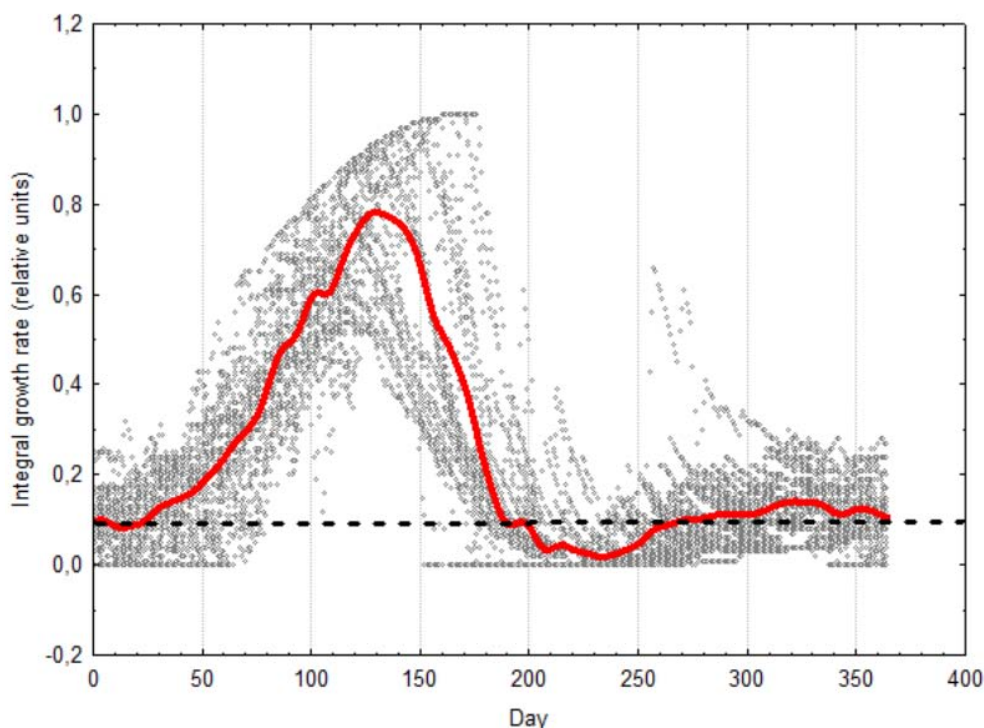


Fig. 4. Average integral growth rate $Gr(t)$ (red line) for calibration period (1982–2004) fitted by negative exponentially-weighted smoothing (McLain 1974). Dashed line corresponds to minimum cambial cell growth rate V_{cr} .

Table 2. Descriptive statistics of simulated tree-ring curves obtained by different values of drainage coefficient Λ . Last column is Pearson correlation between the initial chronology ($\Lambda=0$) and the estimated curve using different values of drainage coefficients.

Value of Λ	Valid N	Mean	Median	Std.Dev.	Skewness	Kurtosis	Pearson's correlation
0.000	23	1.000	1.020	0.307	0.379	−0.593	1.00
0.001	23	1.000	1.000	0.368	0.268	−0.774	0.98
0.002	23	0.999	0.880	0.452	0.488	−0.754	0.96
0.003	23	0.999	0.830	0.544	0.461	−0.968	0.95
0.004	23	0.999	0.820	0.649	0.487	−0.810	0.91
0.005	23	1.000	0.750	0.748	0.539	−0.656	0.92
0.006	23	1.000	0.670	0.885	0.667	−0.751	0.91
0.007	23	1.001	0.640	1.074	0.968	−0.247	0.85

corresponds to an increase of the water deficit by about 5%. Such a change of drainage coefficient was strongly reflected in the estimated tree-ring growth. The primary effect was a lowered median, amplified variance and increased skewness of tree-ring chronology with increased Λ (Table 2, and Fig. 5). The lowered median of growth reflects an increased water deficit in the soil. This result highlights the importance of parameter settings in the VS model, as a higher Λ could result in a more sensitivity of tree growth to precipitation.

4 Conclusions

The process-based VS model skillfully reproduces a time series of a regional *Pinus halepensis* tree-ring chronology for Tunisia as a function of climate alone. The chronology simulated by the model correlates strongly with the original chronology for the calibration period used to tune the model parameters ($r = 0.76$, AD 1982–2004). More important, the model effectively generates a tree-ring chronology for an earlier period of time outside the tuning window ($r = 0.63$, AD 1959–1981). The results suggest that, at least for this species,

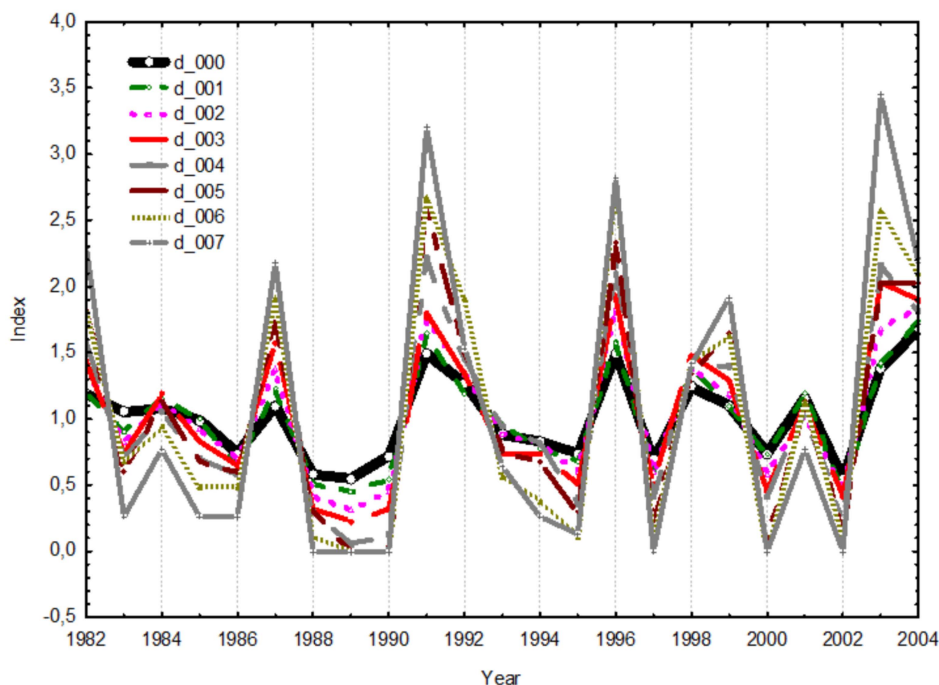


Fig. 5. Simulated tree-ring growth chronologies by different values of drainage coefficients.

daily precipitation, temperature and day length alone are sufficient under the model framework to generate ring-width variations.

The model yields important diagnostic information on the tree-growth response to climate. For example, the model shows that the average duration of the growing season is 191 days, and that on average soil moisture limits tree-ring growth for 128 days and temperature for 63 days in that 191-day window. The model also indicates a huge variability about the mean in such variables as duration of growing season, and leaves open the possibility of a bimodal growth season in some years. The strength of the VS model is its ability to simulate a non-linear tree-growth response to climate changes. In the Mediterranean region and elsewhere such simulations can be used to help explain observed patterns of tree-growth variation in the past and to simulate tree growth under extreme environmental changes. The VS model may also be useful in the climatic interpretation of tree-ring variations when the climate-growth signal is weaker than for the samples used in this study. Good simulation results have previously been reported for such cases (e.g. Vaganov et al., 2006; Shishov et al. 2007; Ivanovsky and Shishov, 2010). Of course, the ability of the model to handle nonlinear climate influence on growth can result in good simulations only when the climate-growth linkage is reasonably strong.

Although primarily, as in this paper, used with conifers, the VS model is also applicable to tree-ring chronologies of angiosperms (hardwood trees). Developers of the model

(E. Vaganov, A. Shashkin and H. Fritts) have successfully used it on hardwoods (unpublished results)

Output from the processes-based VS model includes the partial influence of temperature and precipitation (soil moisture) on tree-ring formation, the water content in the soil during the growing season, and the start and end date of the growing season. Potential applications of this type of information include assessment of likely impact of regional warming on tree-ring indices, and evaluation of the capability of particular tree species to sense climate fluctuations in various seasonal time windows.

VS-modeling and direct cell measurements enable us to estimate cell dynamics of tree-ring formation in this extremely dry Mediterranean environment, and to better understand how tree growth there is controlled by climate. Multi-year natural field studies, including cell dimension measurements, are essential to better understand the dynamics and verify model findings.

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