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TREE-RING AND CLIMATE RELATIONSHIPS FOR *ABIES ALBA* IN THE INTERNAL ALPS

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ABSTRACT

The relationships between the tree-rings of the white fir (*Abies alba* Mill.) and climate in the French internal Alps are indicated by correlation functions. This fir shows an accurate response to climate as well as long term persistence for at least six years (MS=0.18, R_1=0.65, and R_6=0.27). Its growth is strongly influenced by the previous year's climate, especially by prior August rainfall, which enhances ring size, or by high temperatures, which show the opposite effect. The most critical period extends from prior July to prior September. This species responds positively to warm temperature from current January to April, followed by rainfall in May and June, which leads to a longer growth period. A favorable water balance seems to be decisive. *Abies alba* can be affected by frost and seems to prefer a low thermal amplitude as demonstrated by the analysis of the extreme temperature data. Moreover, even a few days of excessive heat can reduce its growth.

Die Beziehungen zwischen den Jahresringen der Weiβtanne (*Abies alba* Mill.) und das Klima in den zentralen französischen Alpen deuten Korrelationen an. Diese Tanne zeigt sowohl eine direkte Reaktion auf das Klima als auch langfristige Auswirkungen über mindestens sechs Jahre (MS=0.18, R_1=0.65, und R_6=0.27). Ihr Wachstum ist stark durch das Klima des vorherigen Jahres beeinfluβt, vor allem durch Regenfälle vor dem ende des monats Juli, die zu einer erhöhten Ringgröβe führt, oder durch hohe Temperaturen, die das Gegenteil bewirken. Die kritischste Periode erstreckt sich von ende Juni bis ende August. Diese Art reagiert positiv auf warme Temperaturen von Januar bis April, gefolgt von Regenfall im Mai und Juni, was zur einer verlängerten Wachstumsperiode führt. Ein günstiges Wasserverhältnis scheint ausschlaggebend zu sein. *Abies alba* kann von Frost beeinfluβt werden und scheint eine niedrigere thermische Amplitude zu bevorzugen, wie die Analyse der extremen Temperaturdaten veranschaulicht. Auβerdem kann ihr Wachstum schon durch wenige Tage übermäβiger Wärme reduziert werden.

On analyse les relations entre les cernes du Sapin pectiné (*Abies alba* Mill.) et le climat au moyen des fonctions de corrélation. Le Sapin montre une bonne réponse au climat et une inertie à long terme sur au moins 6 ans (MS=0.18, R_1=0.65, and R_6=0.27). Sa croissance est fortement influencée par le climat de l'année précédente, en particulier par les précipitations en Août (n-1) qui augmentent les largeurs de cernes, ou par de fortes températures qui montrent simultanément un effet opposé. La période la plus critique va de Juillet (n-1) à Septembre (n-1). Cette essence apprécie des températures chaudes de Janvier (n) à Avril (n), suivies de pluies en Mai (n) et Juin (n), ce qui conduit à une plus longue période de végétation. Un bilan hydrique favorable semble être essentiel au Sapin. Il peut être affecté par le gel et semble préférer une amplitude thermique réduite, comme le montre l'analyse des données de températures extrêmes. De plus, même quelques jours trop chauds peuvent réduire sa croissance.

INTRODUCTION

White fir (*Abies alba* Mill.) is a widely distributed coniferous species in Europe (Rol 1937). Consequently, the forest diseases that have been reported in fir forests raise many problems for foresters and tree physiologists (Cramer and Cramer-Middendorf 1984). Climatic events are known to be involved in this phenomenon (Fourchy 1951). For instance, dry years usually reduce tree growth and, according to several authors, may trigger disease (Becker 1989).

For that reason, it seems important to precisely analyze the influence of climate on white fir growth. Several methods, either ecophysiological (Aussenac 1973, 1975; Becker 1982; Hinckley and Ritchie 1972) or dendroclimatological (Becker 1989; Fritts 1966, 1976; La Marche 1974; Polge 1971; Tessier 1981), can be used for this purpose. Since the latter elucidate the influence of climate over long periods of time, we used dendroclimatological methods to study the ring growth and climate relationships in white fir. A particularly dry growth site was chosen to contrast the results with other studies of this species, which were achieved in milder climates such as Italy (Corona 1983), southeastern Germany (Becker and Giertz-Siebenlist 1970), and France in the Mont Ventoux (Serre Bachet 1986) and the Vosges (Becker 1989).

MATERIALS AND METHODS

Sampling

A forest called “le Bois des Bans” near Briançon (Hautes-Alpes, France), where white fir grows from 1520 meters to 1820 m elevation on north facing slopes ranging from 0° to 40°, was chosen for this study. In 31 plots (one per hectare), 310 cores were taken at breast height with a Pressler borer. The five tallest trees in each plot were sampled, with two cores per tree taken in opposite directions perpendicular to the slope. Eight cores were eliminated, and the 42,406 ring-widths of the 302 remaining cores were measured in our laboratory (Rolland 1993).

Tree-Ring Data

For each core, the average of all the ring-widths (<C>), the mean square (σ^2), and the coefficient of variation (CV) are calculated by the formulas:

$$<C>=\frac{1}{N}\bullet\sum_{i=1}^{i=N}(C_i) \quad = \text{Average of all the rings (0.01mm)}$$

$$\sigma^2=\frac{1}{N-1}\bullet\sum_{i=1}^{i=N}(C_i-<C>)^2 \quad = \text{Mean square (0.01mm)}$$

$$CV=\frac{\sqrt{\sigma^2}}{<C>}\bullet 100 \quad = \text{Coefficient of variation (percent)}$$

where:
C_i represents ring number i.
N is the age of the tree (number of rings).
Mean Sensitivity (MS) is given by:

$$MS = \frac{2}{N-1} \bullet \sum_{i=1}^{i=N} \frac{|C_{i+1} - C_i|}{C_{i+1} + C_i}$$

The autocorrelation coefficients R_k are given by:

$$R_k = \frac{1}{\sigma^2 (N-k-1)} \bullet \sum_{i=1}^{n-k} (C_i - <C>) \bullet (C_{i-k} - <C>)$$

A lag, k, ranging from 1 to 30 years is included in this study, and an average value $<R_k>^2$ is obtained with all the cores.

The growth indices for each core are obtained by using a moving average with seven terms to remove the effect of long-term trends such as the age effect or the influences of human activities. After synchronizing the individual series, a master chronology is built by averaging all the cores (Rolland 1993).

Meteorological Data

The meteorological station of Briançon, at an elevation of 1324 m, has continuously recorded daily precipitation and temperature data since 1947 and solar radiation since 1961. The average annual rainfall for the last 30 years (1961-1990) is 713 mm, and the mean annual temperature is 7.5°C.

Calculation of the Response Functions

Since the first autocorrelation coefficient is high ($<R_1>^2=0.65$), the influence of the previous year is expected to be important. Consequently, twelve months of the prior year, from January to December, are used in addition to the data of January through September during the current year of growth. Thus, 21 months are employed (Fritts 1976). The effects of five parameters are studied separately: (1) total monthly rainfall in mm per month, (2) average monthly temperature (°C), (3) solar radiation (hours per month), (4) average monthly minimum temperature (°C), and (5) average monthly maximum temperature (°C). We calculated the correlation functions instead of the response functions because they are easier to interpret (Blasing et al. 1984). Thus, the correlation coefficients between the indices of growth and the monthly climate data are calculated for each parameter.

RESULTS

Mean Sensitivity and Autocorrelation

Before analyzing the influence of climate, three important tree-ring parameters were calculated: mean sensitivity (MS), the coefficient of variation of the ring-widths (CV), and the autocorrelation coefficients (R_k). The first measure (MS) describes the variability of the high frequency component of the ring-widths due to climatic fluctuations, while the second (CV) represents low frequency variability caused either by climate or by other long term influences.

The third value (R_k) describes the influence of growth during the year n-k on growth during the year n.

The coefficient of variation ranges between 2 and 12 percent, and the repartition curve exhibits a bell shape (Figure 1). Moreover, the mean sensitivity shows a similar pattern, ranging between 0.121 and 0.258 (Figure 2). In comparison, the MS is about 0.3 in Mediterranean regions (Tessier 1982), while in Arizona it can reach 0.6 to 0.8. In Briançon, the average value is 0.179, which is enough to obtain accurate results with the correlation function method.

The autocorrelation coefficients $<R_k>^2$ show a rapid decrease with lag k (Table 1, Figure 3). It appears that the first six R_k coefficients are high enough to completely characterize the autocorrelation because for the order k=6, $<R_6>^2$ equals only 0.27. This phenomenon may be due to several factors. Growth during previous years influences growth of the current year because nondeciduous coniferous species keep their needles for several years, but the efficiency of old

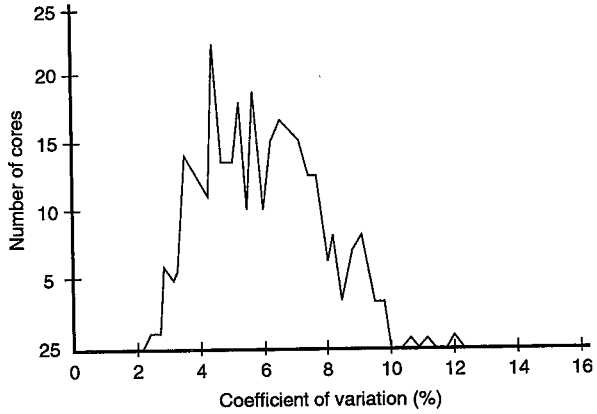

Figure 1. Distribution of coefficients of variation among the 302 *Abies alba* Mill. cores.

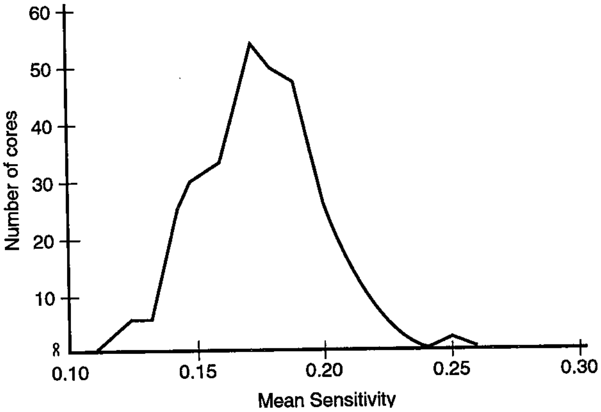

Figure 2. Mean sensitivity of 302 *Abies alba* Mill. cores.

Table 1. Autocorrelation coefficients (r_k^2) for ten lags (k).

k	1	2	3	4	5	6	7	8	9	10
R_k^2	0.65	0.56	0.46	0.38	0.33	0.27	0.23	0.20	0.17	0.14

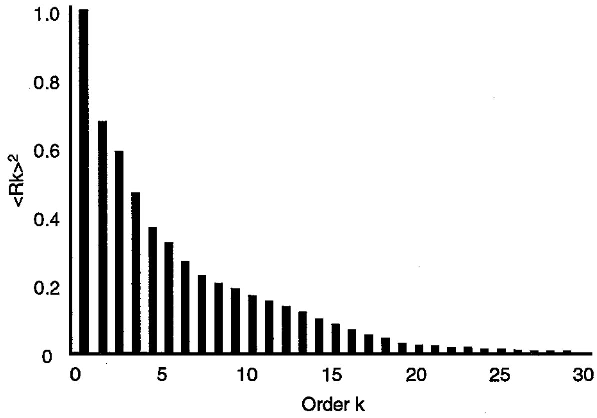

Figure 3. Autocorrelation coefficients, $<R_k>^2$, with order k ranging from 0 to 30 years (average of all the cores).

needles decreases with age. If needles are destroyed by frost or insect attacks, tree growth will be reduced the following year. For instance, young Scots pines attacked by insects recover their normal growth after only one year, whereas older trees (more than 80 years old) need about four years (Laurent-Hervouet 1986). Moreover, snow falling during year n-1 provides water reserves for year n. The buds are also initiated during the previous vegetative period. The development of the root system or the effects of forestry practices such as thinning may also be responsible for long term correlations. All these factors explain why the R_1 value ($<R_1>^2=0.65$) is so important. Consequently, the previous year must be taken into account in time series analysis.

Climatic Effects

Since the rainfall is low in the Briançonnais, this parameter is quite important. The firs react positively to precipitation during their vegetative period, since rainfall in current May and July is positively correlated with growth (Figure 4A). Similarly, rainfall during the previous year has a positive influence from prior July to prior October, particularly in prior August and September. This effect is more extended and accurate than rainfall effects during the year of growth, since rainfall provides water reserves for the following year. Because a lack of rain strongly reduces growth, firs do not tolerate water stress.

Warm springs during the vegetative period are very favorable for growth, especially current February to April and more significantly current March (Figure 4B). In the internal Alps, the winters are long and cold, especially on north facing slopes, so a warm spring may activate the cambium earlier and accelerate snow melt, which may enhance growth (Graumlich 1991).

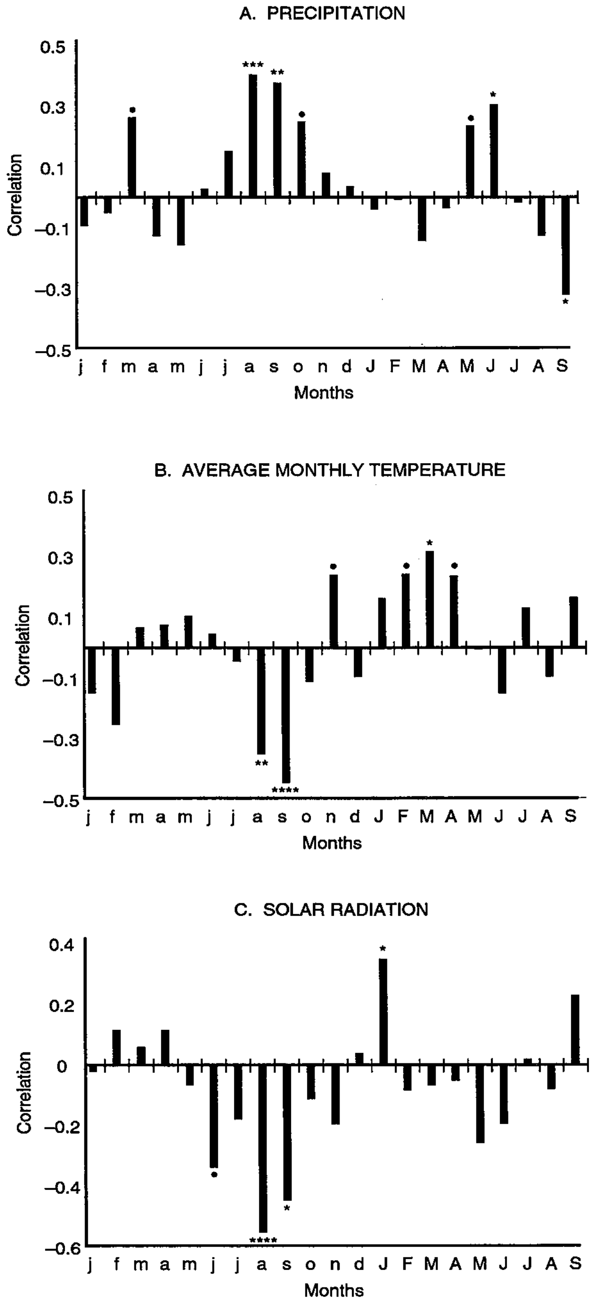

Figure 4. Correlation functions for white fir growth and (**A**) total monthly precipitation, (**B**) mean monthly temperature, and (**C**) monthly solar radiation during the previous and current years. Correlation coefficients that exceed significance levels 0.9, 0.95 0.975, 0.99, and 0.995 are shown respectively by ●, *, **, ***, and ****.

Moreover, the activation of fir buds is sensitive to high temperatures (Aussenac 1975).

Previous-year temperature also plays an important part. Clearly, a warm prior August and September reduces growth the following year. During this period, water reserves in the soil are gradually reduced, since rainfall is not sufficient to offset the transpiration of the trees. Consequently, the firs become increasingly sensitive to the thermal stress. Since current spring frost reduces growth, white fir can be called a frost sensitive species. A warm prior November seems to be favorable, perhaps because it characterizes a mild winter.

Most of the time, high solar radiation (Figure 4C) has a negative effect on fir growth, which contrasts with other species such as larch. Though the duration of sunshine is usually brief on northern slopes, the radiation seems to be at all times sufficient for white fir photosynthesis. Being shade tolerant (Rol 1937), this species does not require a very sunny climate to grow. The influence of solar radiation is essentially the opposite of that of precipitation because high radiation usually implies both low rainfall and warm temperatures. Thus, higher radiation in current May and June reduces growth because rain is decisive during this critical period. This phenomenon is observed more accurately during May to November of the previous year, especially in prior August when the fir requires mild temperatures and sufficient rainfall simultaneously. The favorable effect of solar radiation during current January is probably indirectly due to the warming of the air (Fairbridge 1987).

Since $T_{\bar{X}} = .5\ (T_{min}+T_{max})$, this value describes the temperature influences well. The use of T_{min} and T_{max} separately, however, can provide more detailed information (Figure 5A and B). Thus, the negative influence of warm temperature in current June is clearly due to the role of the maximum values and not to the minimum. Similarly, the negative part played by warmth in prior August or September is more closely linked with maximum temperatures. Consequently, the hypothesis of an increase in transpiration is confirmed: higher temperature during the day increases the vapor pressure deficit of the air and may lead to thermal stress and stomatal closure.

In contrast, the positive effect of current July temperature is not due to the maximum temperature but to the increase of the minimum. The same phenomenon appears in prior November, which means that the nights are milder and the thermal amplitude reduced. The continental trend of the climate seems unfavorable to fir growth, which may be affected by frost. High minimum temperatures in previous May or June also are favorable, probably because the buds are inhibited by a cold period.

Both minimum and maximum temperature data help analyze correlations with mean temperature. It also would seem interesting to investigate the part played by absolute daily temperature, since a few days with frost can destroy the cambium and modify the growth even when the monthly average is normal. (Some information is lost by averaging the 31 values over a complete month.) This method requires using daily values to detect extremes. It reveals some phenomena that cannot be found with monthly averages. Thus, a few days in prior December with high maximum temperatures can greatly reduce growth the following year, perhaps because the warming activates tree respiration and the consumption of metabolical reserves that should have been used during the following spring (Figure 5C). Only a few days with high maxima in spring are efficient, because they accelerate activation of the buds. In contrast, the limiting effect of February frost described by Becker (1989) does not appear here, but a late frost during the day in current July strongly affects the firs.

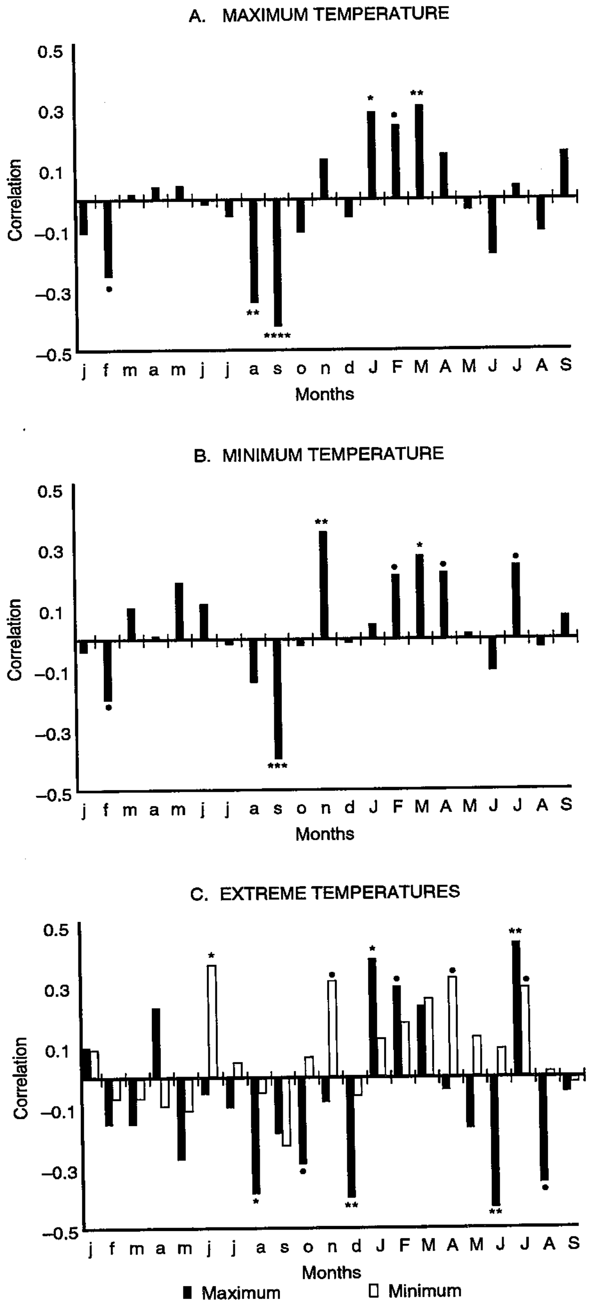

Figure 5. Correlation functions for white fir growth and (**A**) maximum temperature, (**B**) minimum temperature, and (**C**) extreme temperatures. Correlation coefficients that exceed significance levels 0.9, 0.95, 0.975, 0.99, and 0.995 are indicated repsectively by ●, *, **, ***, and ****.

CONCLUSIONS

This dendroclimatic analysis carried out on white firs in severe climatic conditions of drought reveals many elements of the ecology of this species. A mean sensitivity of 0.18 indicates a response to climatic factors, and the autocorrelation coefficients demonstrate low frequency effects for about six years. The climate during the year prior to growth is important because $<R_1>^2=0.65$. Moreover, its influence is greater than that of the year of growth.

Many coefficients of the correlation functions are highly significant and have important ecophysiological implications. White fir is a shade tolerant species and does not require high insolation, even on north facing slopes. On the contrary, high insolation is unfavorable. The species seems to prefer a reduced temperature amplitude.

White fir strongly suffers from deficient rainfall and excessive temperatures in prior August and September. This is the most critical period for this species, since water reserves are at their lowest point at the end of the summer. Consequently, the water balance appears to be the most relevant factor in radial growth. Hot and dry days may provide a signal to the tree by inducing strong water stress that causes the fir to close its stomates to reduce transpiration. We may also assume that, during the hot period, radial growth is reduced because the tree, in order to absorb more water, develops its root system instead of producing wood for the trunk or the branches.

Because growth is strongly linked to climate, we attempted to describe the growth indices with linear multiple regression (Becker 1989). The annual climatic values of the current year explain only 30 percent of the variability in ring width. Monthly data, however, provide better results. For instance, R^2 equals 0.350 by using eight monthly values of precipitation and average temperature, and R^2 reaches 0.463 by adding maximum and minimum temperatures. This result confirms that extreme data provide more information than average values. Furthermore, solar radiation is also strongly linked to the tree rings because the R^2 value reaches 0.740 with the use of precipitation, average temperature, and radiation.

The best model includes the climatic data of both the current and previous years, which produces an R^2 of 0.894. This equation is:

$$I = 6.1947\,(T_7) + 0.0059\,(R_9) + 0.1422\,(P_6) + 0.0672\,(R_{10}) - 4.3694\,(U_9) + 2.9004\,(U_5) + 0.0532\,(P_{12}) + 0.0453\,(R_1) + 3.2289$$

where:

T_7 = current July temperature

R_9 = prior September precipitation (reserves)

P_6 = current June precipitation

R_{10} = prior October precipitation (reserves)

U_9 = prior September temperature (rapid end of summer)

U_5 = prior May temperature (warm May)

P_{12} = current December precipitation (rapid end of current summer)

R_1 = prior January precipitation (snow melt)

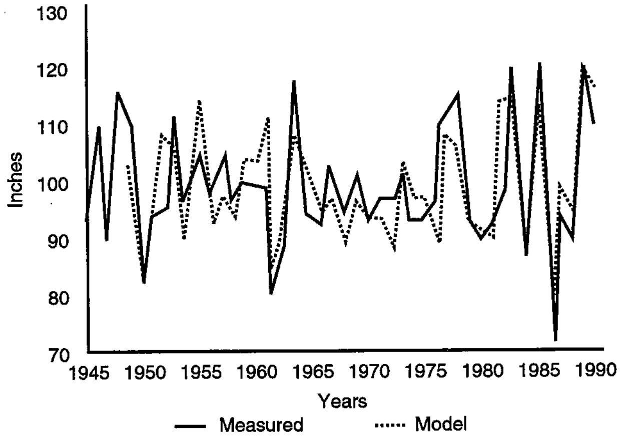

Figure 6. Time series analysis of white fir ring growth in the Alps.

Table 2. Effects of extreme climatic events on white fir radial growth.

Year	Ring Growth	Climatic Variable	Period	Difference	Cause
1985	+++	Precipitation	May -> Aug.	+29%	favorable rainy summer
1983	+++	Precipitation	May -> Aug	+38%	favorable rainy summer
		Precipitation	Apr - May	+220%	refill soil reserves
1964	+	Temperature	Jan -> May	+1.3°C	hot spring before growth
		Temperature	Jan - Feb	+3.0°C	no frost damage
1962	– –	Precipitation	May -> Aug	–59%	severe drought in summer
1986	– – –	Precipitation	May -> Aug	–39%	severe drought in summer
		Temperature	Jan -> Apr	–2.0°C	excessively cold spring
		Temperature	Feb.	–4.0°C	frost damage

As can be seen in Figure 6, the dotted line that represents the calculated values is quite similar to the measured ring widths.

The influence of extreme climatic events on the relationships revealed by the time series analysis are analyzed by subtracting the "normal" climatic data from the measured extreme values. These differences during critical periods are expressed in percentages or degrees C for the major positive or negative tree-growth values in Table 2.

Given the results of this time series analysis, it should be possible to use the ring widths for reconstructing aspects of past climate in the Hautes-Alpes (Schweingruber et al. 1991). Because a similar study was carried out on *Pinus uncinata* in the same area, combined use of the two coniferous species should provide more accurate results.

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