Source: Heinrich I, Gärtner H, Monbaron M, Schleser G (eds.) (2006) TRACE - Tree Rings in Archaeology, Climatology and Ecology, Vol. 4: Proceedings of the DENDROSYMPOSIUM 2005, April 21st – 23rd 2005, Fribourg, Switzerland. Schriften des Forschungszentrums Jülich, Reihe Umwelt Vol. 61, p. 152 – 164.

Impact of the drought in 2003 on intra- and inter-annual stem radial growth of beech and spruce along an altitudinal gradient in the Black Forest, Germany

H.P. Kahle

Institute for Forest Growth, University Freiburg, Tennenbacherstrasse 4, 79085 Freiburg, Germany

Email: Hans-Peter.Kahle@iww.uni-freiburg.de

Introduction

Measuring changes in stem dimension in high time-resolution is a suitable means to trace intra-annual diameter growth of trees as well as to monitor the hydrological status of tree stems. Tree growth rates vary considerably during a growing season and also from year to year (Mitscherlich *et al.* 1996, Abetz *et al.* 1993, Künstle 1995, Mäkinen *et al.* 2003). The term growth is defined as the increase in size by assimilation of material into the living organism (*c.f.*, Merriam-Webster 2005). Hence, changes in stem diameter due to growth are non-reversible, in contrast to the diurnal rhythm of contraction and expansion of tree stems which is due to shrinking and swelling processes associated with changes in trunk hydrology (Deslauriers *et al.* 2003, Zweifel *et al.* 2000). Continuous ongoing dendrometer measurements provide up-to-date insight into the current level of growth and the water status of tree stems. Recent studies focussing on the impact of the severe drought in the year 2003 on tree growth have shown the significant value growth monitoring based on dendrometer measurements can provide to the timely assessment of forest condition (Anders *et al.* 2004, Dietrich *et al.* 2004).

Drought resistance and resilience of European beech (*Fagus sylvatica* L.) in view of the anticipated climatic changes has recently been discussed controversially (e.g., Rennenberg *et al.* 2004, Kölling *et al.* 2005). With the comparison of intra- and inter-annual growth responses of beech and Norway spruce (*Picea abies* (L.) Karst.) during and after the severe drought conditions of summer 2003 this study aims at providing further empirical evidence to substantiate this discussion.

Material and methods

Dendrometer data

Beech and spruce sample trees have been continuously monitored over a several years period by means of point dendrometers (Fig. 1). Measurement data of sample trees on three sites along an altitudinal gradient at the western slope of the Black Forest are analysed (450 m, 750 m, and 1.250 m above sea level (asl), see figure 2).

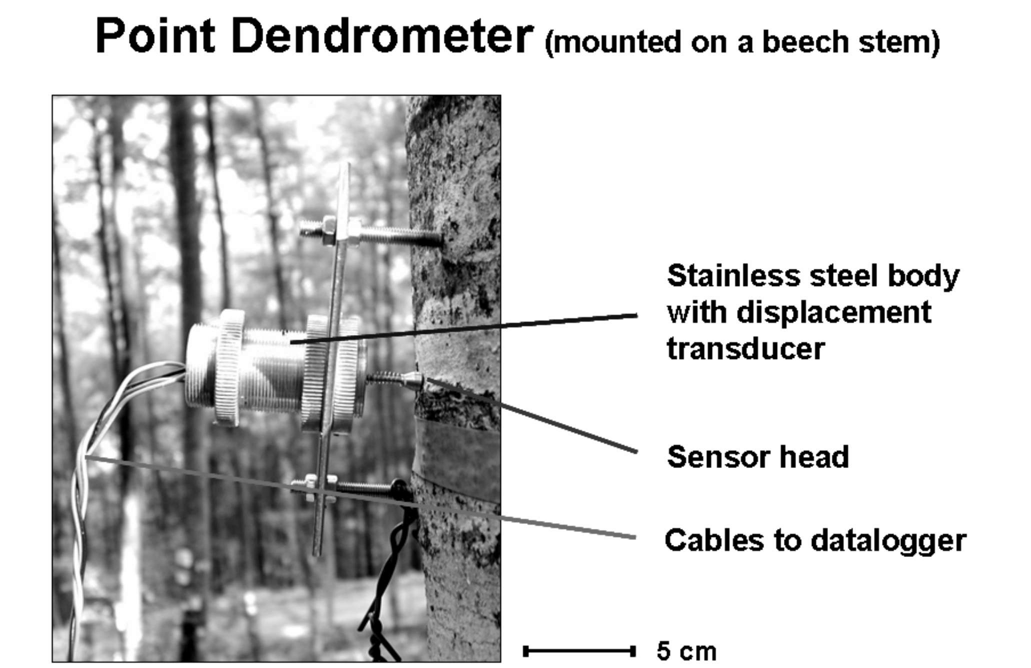


Figure 1: Point dendrometer, Model IWW. Sensor: linear displacement transducer. Height of measurement: 1.3 m (breast height).

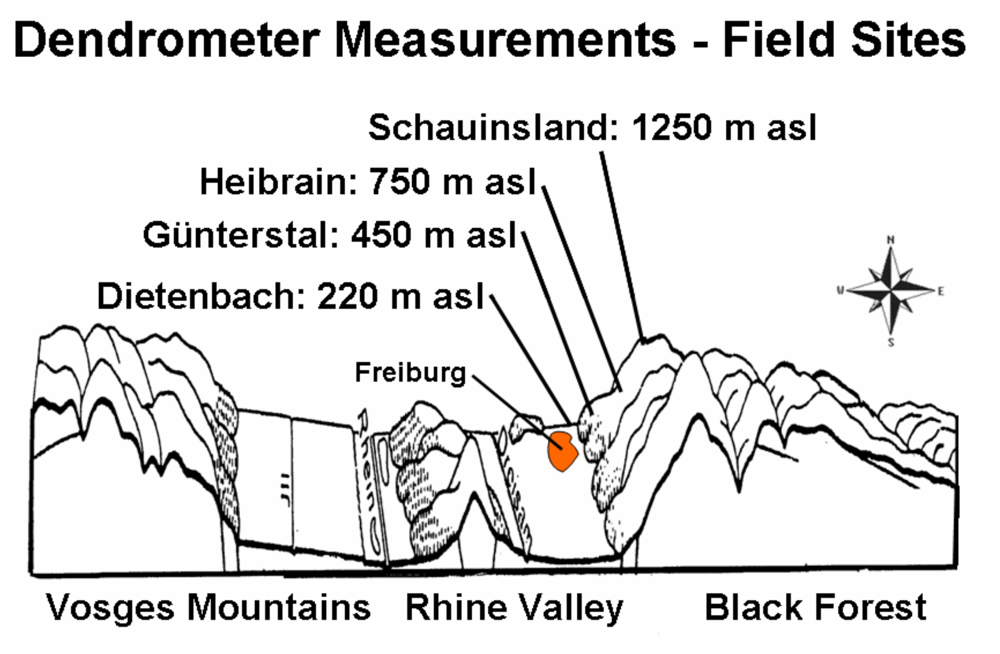


Figure 2: Sketch of the research area with locations of the four field sites in the Rhine Valley and at the western slope of the Black Forest running from 220 m to 1.250 m asl.

Data from an additional nearby site in the Rhine valley, Dietenbach (220 m asl) where beech and oak (*Quercus robur*) sample trees are monitored is as well included in the analyses.
The sites of the Black Forest altitudinal gradient are similar with respect to site type and aspect (northeast). All forest stands under study are mature, mixed-species stands. At each field plot several sample trees belonging to different crown classes are equipped with dendrometers. For the purpose of this study only sample trees that belong to the crown class pre-dominant and dominant are considered. The age of the sample trees is approximately 60-70 years at sites DIE, GUE, and SCH, and approximately 80 years at site HEI. For each site and species the number of sample trees included in the analyses is n = 2 trees. The dendrometer data time series span from 1999-2004 (Günterstal GUE, Heibrain HEI), 2000-2004 (Schauinsland SCH), and 2002-2004 respectively (Dietenbach DIE). The dendrometer measurement time interval ranges from 15 min (DIE) to 30 min. For the analyses the time series data have been aggregated to daily means. The presented mean time series are in each case based on a constant set of trees.

Climate data
Time series of measured daily average air temperature and daily precipitation sum of two measurement stations have been used for the analyses:

- Karlsruhe: Rhine Valley, 115 m asl, observation period: Jan 1895 - Sep 2004 (Deutscher Wetterdienst DWD)
- Schauinsland: Black Forest, 1205 m asl, observation period: Jan 1994 – Sep 2004 (Umweltbundesamt UBA).

Methods of data analysis
Besides radial/diameter growth dendrometer data reflect reversible changes due to stem hydrological changes. For this reason the data measured with point dendrometers are termed “radial displacement” (RadDisp), rather than “radial growth”. In order to suppress high frequency variation and to amplify medium- and long-term oscillations the individual tree time series of radial displacement were smoothed using a symmetric 11-day running average. For the analysis of the daily rate of change of radial displacement (Rate of RadDisp or RRD) the data on daily differences once more was smoothed using a cubic smoothing spline with a 50% frequency cut-off of 30 days.
Three cardinal points of the RRD time series are analysed and discussed:

- the beginning of radial growth is the date at which the RRD-curve crosses the zero line (from negative to positive) during the early growing season,
- the date of RRD culmination max is the date at which the maximum RRD occurs,
- the end of radial growth is the date at which the RRD-curve crosses the zero line (from positive to negative values) during the late growing season.

To investigate the radial growth response to the drought in the year 2003 the RadDisp data of the years 2003 and 2004 are related to the average course of RadDisp in a several year lasting reference period comprising the data of all other available years in the specific data set.

Results

Baseline climatic conditions and anomalies of air temperature and precipitation in 2003

Data on mean air temperature and precipitation sum at the climate measurement stations Karlsruhe and Schauinsland for the common overlap period 1992-2002 are given in Table 1. Mean air temperature at the low elevation station Karlsruhe is 5.4 K and 6.4 K higher than at the high elevation site over the whole year and for the months May-September respectively. Precipitation sum at the high elevation site Schauinsland is 2.6 and 2.5 times larger over the whole year (Dec-Jan) and for the growing season (May-Sep) respectively.

Table 1: Climate data for the period 1994 to 2002 and for the year 2003 at climate stations Karlsruhe (data soruce: Deutscher Wetterdienst DWD) and Schauinsland (data source: Umweltbundesamt UBA) (top: mean air temperature (Tp), bottom: precipitation sum (Pr)).

Station	**Season**	**Period/Year**	**Mean temperature** °C	**Tp-Anomaly** K	
Karlsruhe	Jan-Dec	1994 - 2002	11.4		
(Rhine Valley,		2003	11.9	0.5	
115 m asl)	May-Sep	1994 - 2002	18.1		
		2003	20.3	2.2	
Schauinsland	Jan-Dec	1994 - 2002	6.0		
(Black Forest,		2003	7.2	1.2	
1.205 m asl)	May-Sep	1994 - 2002	11.7		
		2003	14.8	3.1	
			Precipitation sum	**Pr-Anomaly**	
			Mm	Mm	%
Karlsruhe	Jan-Dec	1994 - 2002	813		
(Rhine Valley,		2003	561	252	31
115 m asl)	May-Sep	1994 - 2002	352		
		2003	245	107	31
Schauinsland	Jan-Dec	1994 - 2002	2142		
(Black Forest,		2003	1488	654	31
1.205 m asl)	May-Sep	1994 - 2002	894		
		2003	532	362	40

The year 2003 was extraordinarily warm and precipitation records were far below average at both stations. At the Schauinsland site the increase in mean seasonal (May-Sep) air temperature reached a maximum with +3.1 K. At the same time precipitation was reduced to 30-40 % of normal.

A comparison of the weather conditions in the year 2003 with those of other years characterized by above average air temperatures and below average precipitation sums during the period 1895 to 2002 was possible for the Karlsruhe station (Fig. 3).

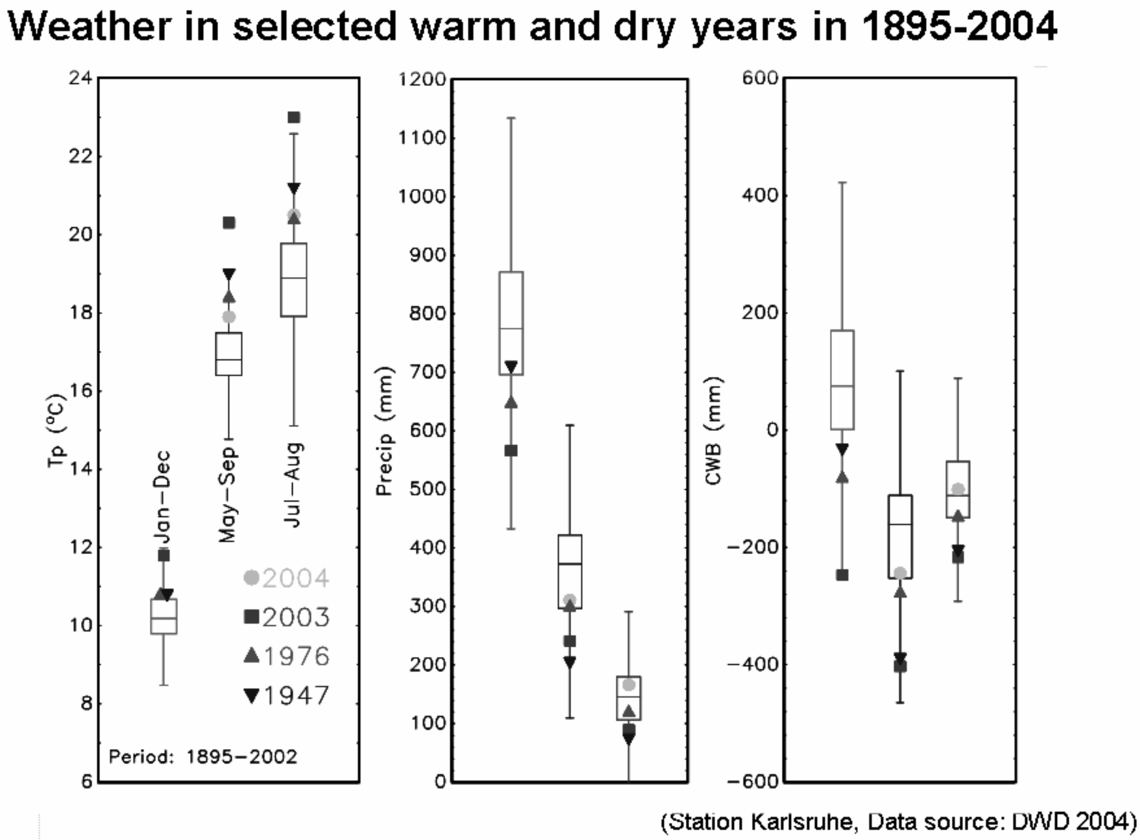


Figure 3: Box plots of weather conditions in selected warm and dry years at climate station Karlsruhe. Left figure: mean air temperature (Tp), centre figure: precipitation sum (Precip), right figure: climatic water balance (acc. to Thornthwaite and Mather 1955, 1957). The three boxes in each figure represent: left: Jan-Dec, centre: May-Sep, right: Jul-Aug. The boxes indicate the range of 50 % of the observations during the reference period 1895-2002 (horizontal line: median). The whiskers represent the empirical 95-percentil.

According to mean air temperature the year 2003 was unparalleled by the other warm years 1976 and 1947 for all three periods (Jan-Dec, May-Sep, Jul-Aug). Precipitation in the year 2003 was lower than in the other two years, however growing season and late summer precipitation in 1947 was slightly lower than in 2003. Due to the high air temperature anomalies and large precipitation deficits the climatic water balance (acc. to Thornthwaite, Mather 1955, 1957) was lower in 2003 than in the other two years, and reached a minimum with less than -400 mm when referred to the growing season.

Level of radial growth

Figures 4-6 show the time series of RadDisp (top) and of the rate of change of RadDisp (bottom) for spruce and beech at the three Black Forest sites.

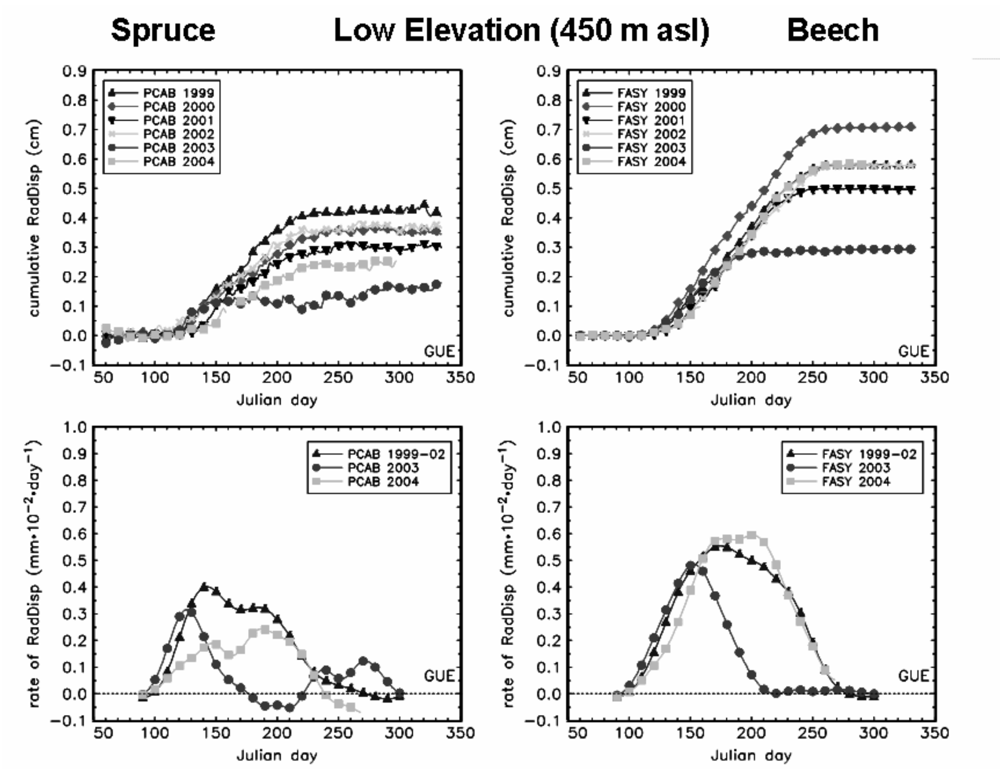


Figure 4: Smoothed (11-day running average) daily dendrometer data versus day of the year for the low elevation site Günterstal (GUE). Top: cumulative radial displacement (RadDisp), bottom: rate of change of radial displacement (smoothed with spline). Left: Norway spruce (PCAB), right: European beech (FASY).

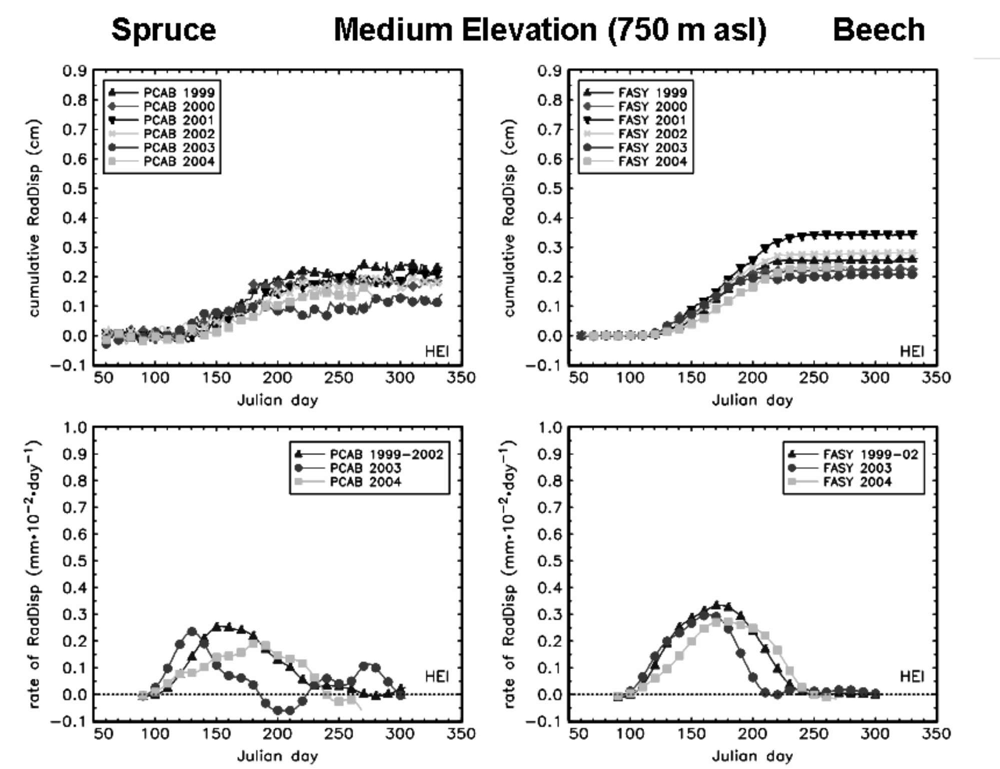


Figure 5: Dendrometer data, medium elevation site Heibrain (HEI). See explanation figure 4.

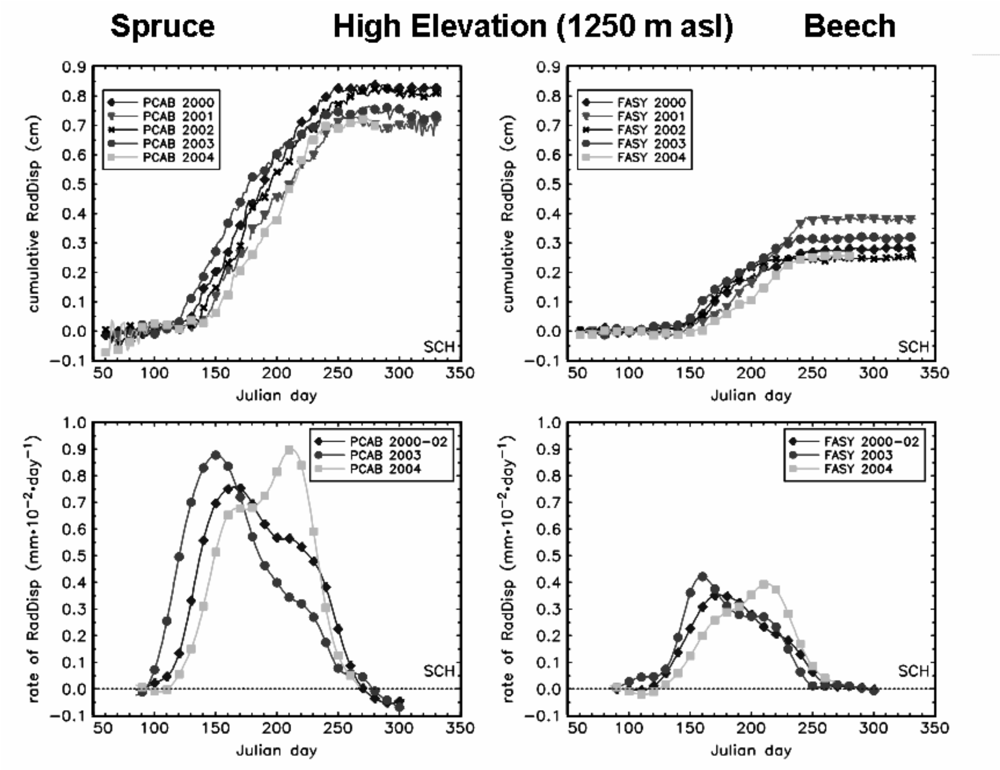


Figure 6: Dendrometer data, high elevation site Schauinsland (SCH). See explanation figure 4.

As can bee seen in the upper plots of figures 4 to 6 there is considerable variation in the mean level or RadDisp between the sites and between the two species. Whereas at the low elevation site (GUE) the beech sample trees grew faster than the spruce sample trees (Fig. 4) the mean level of growth of the sample trees of both species was roughly equal at site HEI (Fig. 5). At the high elevation site (SCH, Fig. 6) the mean level of growth of the spruce sample trees was superior to that of beech.

Beginning, end and length of growing season

During the period 1999-2002 beginning of radial growth occurred in the spruce and beech sample trees simultaneously at day 98 at site GUE and at day 101 at site HEI respectively (Tab. 2). At the high elevation site (SCH) growth of the spruce sample trees was advanced compared to beech: growth started in the mean at day 98 and at day 103 respectively. End of radial growth of the beech sample trees at the medium and high elevation sites (HEI and SCH) occurred in the mean 20 days, and 4 days respectively earlier than that of the spruce sample trees. The growing season of the beech sample trees was at the low elevation site (GUE) 7 days longer, and at the sites HEI and SCH 20 days, and 9 days respectively, shorter than for the spruce sample trees (Tab. 3).

Date of maximum rate of radial displacement

In the mean over the period 1999-2002 the date of maximum rate of radial displacement for the spruce sample trees from the low to the high elevation site was day 142, 154 and 166 respectively. Nearly independent of elevation the beech sample trees reached their maxima around day 173/174 (Tab. 2).

Table 2: Date of begin and end of radial growth and of maximum rate of radial displacement.

Species	Site	Begin		Maximum rate		End	
		1999-2002	2003	1999-2002	2003	1999-2002	2003
		day of year					
PCAB	GUE	98	91	142	126	272	177
	HEI	101	93	154	130	270	186
	SCH	98	93	166	151	269	278
FASY	GUE	98	93	174	153	279	214
	HEI	101	96	174	164	250	211
	SCH	103	92	173	159	265	252

Table 3: Number of growing days derived from dendrometer data.

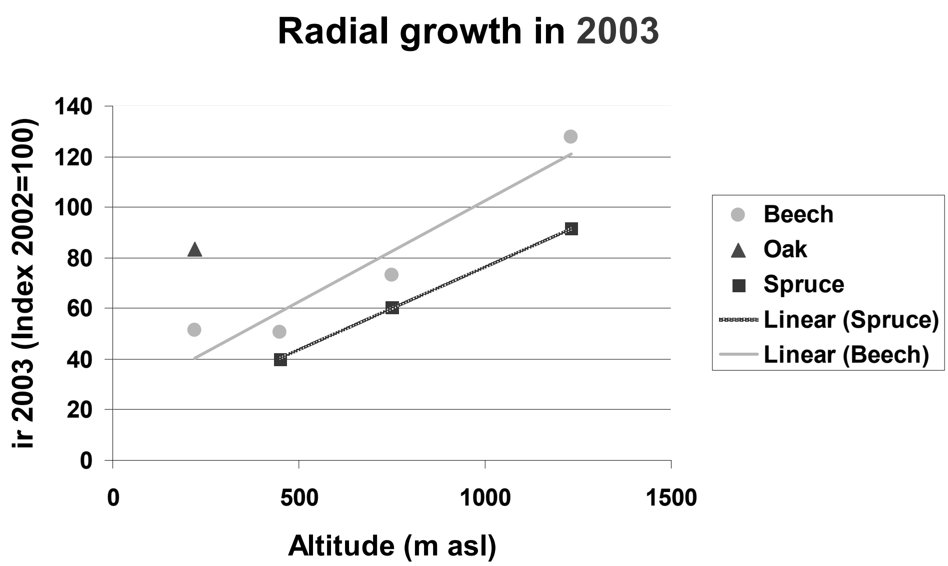
Species	Site	Days		2003 rel. to 1999-2002
		1999-2002	2003	%
PCAB	GUE	174	86	49
	HEI	169	93	55
	SCH	171	185	108
FASY	GUE	181	121	67
	HEI	149	115	77
	SCH	162	160	99

Level of radial growth in 2003

The increased temperatures accompanied by deficits in precipitation in 2003 severely affected radial growth of both species at the low and medium elevation sites: radial growth of the spruce sample trees was reduced by 57 % (GUE) and by 40 % (HEI) as compared to the mean level during the period 2000-2002, for the beech sample trees it was 51 % and 28 % respectively. At the high elevation site (SCH) radial growth of the spruce sample trees was only slightly reduced by 4 %, and for beech it was slightly increased by 5 % (Fig. 6). Reduction in radial growth is paralleled by a shortening of the growing season which was reduced to 49-55 % for the spruce and 67-77 % for the beech sample trees at sites GUE and HEI respectively (compared to the period 1999-2002) (Tab. 2). The level of radial growth in 2003 in relation to the one in 2002 is plotted versus altitude of the site in the upper half of figure 7.

Intra-annual course of growth in 2003

Radial growth of the Norway spruce and beech sample trees in 2003 started earlier at all research sites compared to the reference period. After initiation radial growth in 2003 is accelerated especially in Norway spruce (Fig. 4 to 6). The date at which the maximum rate of RadDisp occurred is advanced in 2003 as compared to the reference period: in spruce by 15 to 24 days and in beech by 10 to 21 days (Tab. 1). The end of radial growth was in 2003 even more advanced: for the spruce sample trees at the medium and low elevation sites by 84-95 days, and for beech by 39-65 days respectively. However, the increase in the rate of RadDisp after day 220 at the medium and low elevations sites might indicate, that spruce has reactivated growth at the late growing season before growth finally ended. At the high elevation site cessation of radial growth of the spruce sample trees was delayed by 9 days.



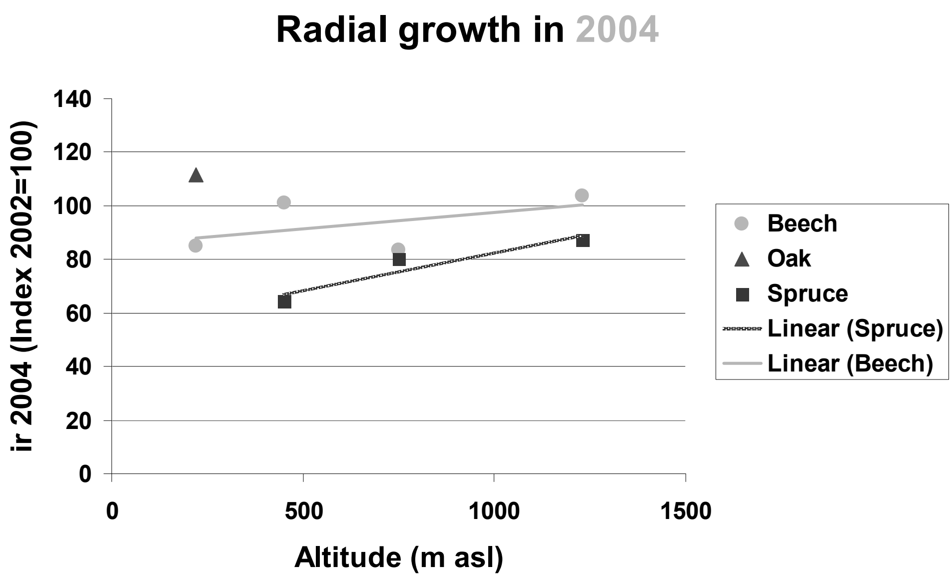


Figure 7: Indexed radial growth in 2003 (top) and 2004 (bottom) versus elevation of the site.

The rates of RadDisp expressed as percentage of the maximum rate during the reference period are displayed in figure 8. The reduction in mean level of growth in 2003 is mainly caused by the shortening of the growing season than by a reduction in the maximum rate of radial displacement.

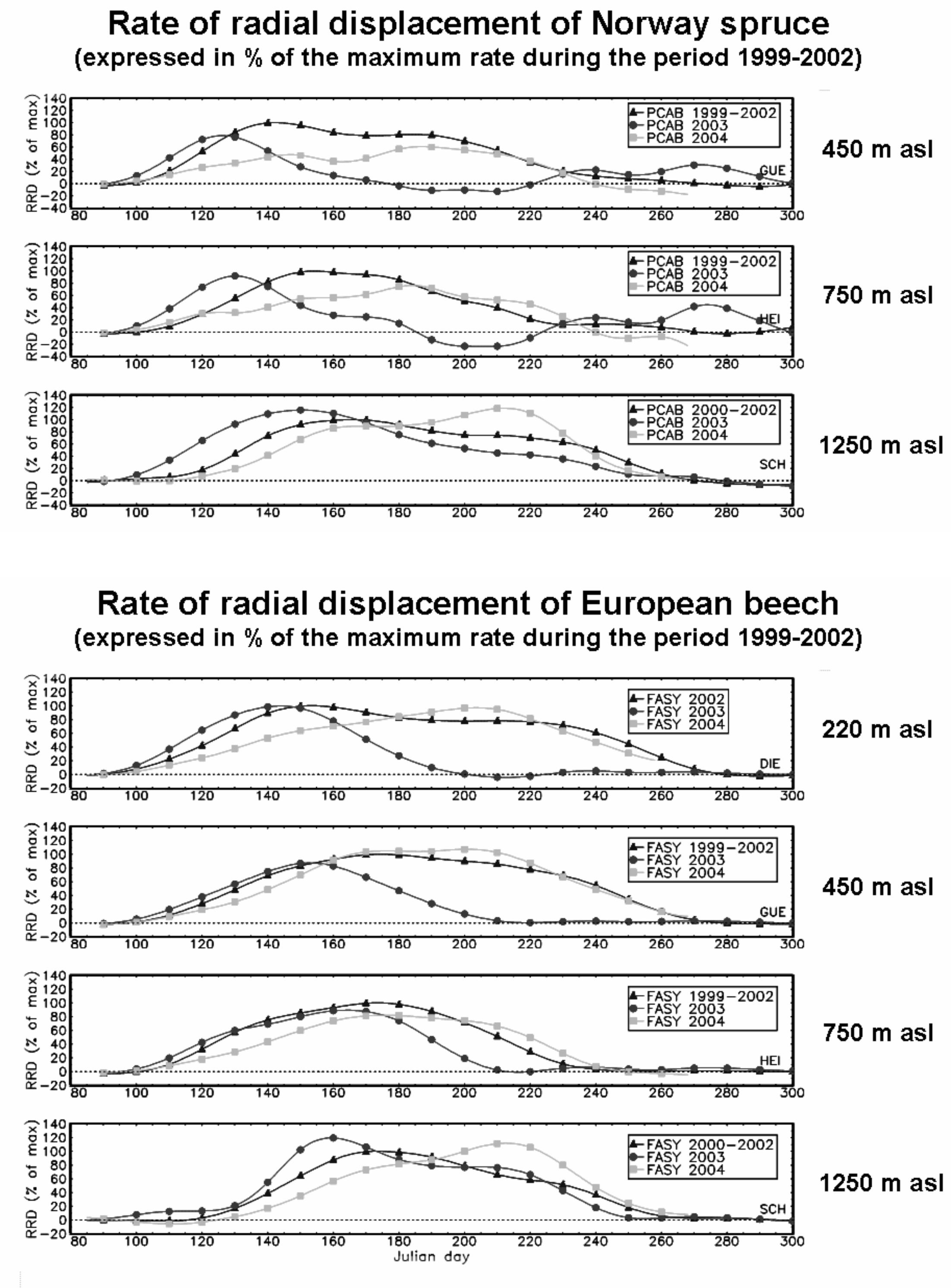


Figure 8: Rate of radial displacement (RRD) versus day of the year of Norway spruce (PCAB, top) and European beech (FASY, bottom) at the research sites.

Level of growth in 2004

Whereas beech radial growth recovered in the year following the severe drought at the low and medium elevation sites to 83-98 % of the reference level (mean of 2000-2002), spruce growth in 2004 was still reduced to a level of 70-79 %. The level of radial growth in 2004 in relation to the one in 2002 is plotted versus altitude of the site in the bottom half of figure 7.

Discussion

Critical evaluation of the data

The number of sample trees used in the analyses is quite low. Each presented curve is at least based on two sample trees. However, the weakness of lacking more replications in sample trees is attenuated by the high precision of the dendrometer data. Highly significant inter-series correlations among the individual tree dendrometer measurement time series indicate high precision of the assessed temporal signals.

Critical evaluation of the methods

The measurement data were pre-processed before the analyses by a one- respectively two-step smoothing procedure as described in the methods section. Whereas the symmetric running average filter applied in the first step only affects the signal amplitudes, the applied smoothing spline function could also produce unwanted phase-shifts. The flexibility of the spline function has been optimized so that most of the medium-term (5 days < x < 30 days) variations are preserved whereas high- as well as low-frequency variations are largely attenuated. The degree of phase-shift was visually checked so that it should not severely affect the results. Another aspect of the data pre-processing is related to end-fit problems of the applied smoothing filters. These could lead to distorted fluctuations at the beginning and end of the curves. The somewhat strange course of the RRD curves for spruce of the sites GUE and HEI in the year 2003 after day 260 (Fig. 8) could partially be due to this effect.

Critical evaluation of the results

The results concerning the dates of beginning and end of radial growth have been achieved by applying the respective definitions given in the methods sections. It is well known from literature that the cambial activity can hardly be tracked by dendrometer measurements (Mäkinen *et al.* 2003, Zweifel *et al.* 2000). A comparison of the results of this study with phenological data on the occurrence of May shoot of Norway spruce at site Schauinsland (Henhappl 2004, unpublished data) revealed a substantially earlier onset of radial growth according to the definition applied here than expected from the phenological data. However, by applying a different definition of beginning of radial growth Abetz *et al.* (1993) found at the same site (SCH) a close relation between the occurrence of May shoot and the beginning of radial growth derived from dendrometer data.

Since the precision of the temporal signal of the dendrometer data is high, the variation in level of growth between the different years of the observation period should be reliably represented. This also holds for the comparison of the performance in radial growth between the two investigated tree species, since these comparisons are based on the time series data.

Due to limitations in the data structure it was in this study not possible to evaluate the effects of and possible interactions between the factors tree age, growth level, and elevation of the site on inter- and intraannual radial growth, since these factors are confounded in the data base.

Summary

The main results of this study can be summarized as follows:

- The record year 2003 was extraordinarily warm over the whole year and especially during the growing season: air temperature anomalies (May-Sep) were as large as +2.2 K at the low elevation site and +3.1 K at the high elevation site. The warm weather in 2003 was accompanied by exceptionally large precipitation deficits: -69 % at the low elevation site and -60 % the high elevation site (May-Sep). Water availability in the year 2003 as indicated by the climatic water balance was at the low elevation site distinctly lower than in the years 1947 and 1976.
- For the beech sample trees the period during which radial growth occurs is longer at the low elevation site than at the high elevation site, which is mainly due to delayed growth cessation in fall.
- Radial growth of the spruce sample trees at the low elevation site was more severely affected by the drought in the year 2003 than that of the beech sample trees (-60 % and -50 % respectively; reference: mean of 2000-2002). Reduction of radial growth in the year 2003 is paralleled by a shortening of the season of radial growth which was at the low and medium elevation sites reduced by ~50 % for the spruce and by ~30 % for the beech sample trees.
- At the high elevation site radial growth was only slightly affected by the exceptional weather conditions in the year 2003: -5 % for the spruce and +5 % for the beech sample trees (reference: mean of 2000-2002).
- Whereas beech radial growth recovered in the year following the severe drought at the low and medium elevation sites to 80-100 % of the reference level (mean of 2000-2002), spruce growth in 2004 was still reduced to a level of 70-80 %.

Acknowledgements

I am grateful to Ms Eberling and Mr Meinhard, both Umweltbundesamt Messstelle Schauinsland, for providing the climate data of the measurement station Schauinsland and to Felix Baab and Albert Fehrenbach, both Institute for Forest Growth University Freiburg, for the continuous maintenance of the field measurements.

References

Abetz, P., Künstle, E., Wolfart, A. (1993): Jahresgang des CO_2-Gaswechsels und der Transpiration von solitären Fichten in den Hochlagen des Südschwarzwaldes in kontrollierter Standortsluft mit und ohne Ozonbelastung. *KfK-PEF* 101: 155 p.

Anders, S., Beck, W., Lux, W., Müller, J., Fischer, R., König, A., Küppers, J. G., Thoroe, C., Kätzel, R., Löffler, S., Heydeck, P., Möller, K. (2004): Auswirkung der Trockenheit 2003 auf Waldzustand und Waldbau. Eberswalde, *Zwischenbericht, BMVEL 533-7120/1*, BFH Hamburg: 109.

Deslauriers, A., Morin, H., Urbinati, C., Carrer, M. (2003). Daily weather response of balsam fir (*Abies balsamea* (L.) Mill.) stem radius increment from dendrometer analysis in the boreal forests of Québec (Canada). *Trees - Structure and Function* 17: 477-484.

Dietrich, H.P., Raspe, S., Schubert, A. (2004): Trockenheit 2003 war nicht die einzige Ursache für starke Zuwachsverluste. Beobachtungen zur Reaktion von Baumkronen, Belaubung und Durchmesserzuwachs der Waldbäume im Jahr 2003. *LWF-Aktuell* 43: 14-16.

Kölling, C., Walentowski, H., Borchert, H. (2005). Die Buche in Mitteleuropa: Eine Waldbaumart mit grandioser Vergangenheit und sicherer Zukunft. *AFZ/Der Wald* 60: 696-701.

Künstle, E. (1995): Beginn, Verlauf und Ende des Dickenwachstums von Solitär-Fichten auf dem Schauinsland bei Freiburg in den Jahren 1989 bis 1993. *Forstliche Forschungsberichte München* 153: 24-39.

Mäkinen, H., Nöjd, P., Saranpää, P. (2003): Seasonal changes in stem radius and production of new tracheids in Norway spruce. *Tree Physiology* 23: 959-968.

Merriam-Webster Online (2005): http://www.m-w.com/ (information retrieved July 10 2005).

Mitscherlich, G., Moll, W., Künstle, E., Maurer, P. (1966): Ertragskundlich-ökologische Untersuchungen im Rein- und Mischbestand: VI. Zuwachsbeginn und -ende, Stärkeänderung und jährlicher Durchmesserzuwachs. *Allgemeine Forst- und Jagdzeitung* 137: 72-91.

Rennenberg, H., Seiler, W., Matyssek, R., Geßler, A., Kreuzwieser, J. (2004): Die Buche (*Fagus sylvatica*) - ein Waldbaum ohne Zukunft im südlichen Mitteleuropa? *Allgemeine Forst- und Jagdzeitung* 175: 210-224.

Thornthwaite, C.W., Mather, J.R. (1955): The water balance. *Publ. in Climatology - Drexel Inst. of Tech., Lab. of Climatology*, Vol. 8, No. 1: 104 p.

Thornthwaite, C.W., Mather, J.R. (1957): Instructions and tables for computing potential evapotranspiration and the water balance. *Publ. in Climatology - Drexel Inst. of Tech., Lab. of Climatology*, Vol. 10, No. 3: 308 p.

Zweifel, R., Item, H., Häsler, R. (2000): Stem radius changes and their relation to stored water in stems of young Norway spruce trees. *Trees - Structure and Function* 15: 50-57.