Chapter 2
Climatic Condition at Three Beech Forest Sites in Central Germany

O. Panferov, H. Kreilein, H. Meesenburg, J. Eichhorn, and G. Gravenhorst

2.1 Climate of Germany

Climate is one of the major factors controlling the growth and functioning of plant ecosystems in general and of beech forests in particular. In the present Chapter climatic conditions at three experimental beech forest sites are described.

The territory of Germany extends for about 8° (55°–47°N) from the coastal line of the North and Baltic Seas to the Alps, within the range of maritime temperate climate sub-zones Cfb and Cwb according to Koeppen classification (e.g. McKnight and Hess 2000). It is described as a transition zone between the maritime climate of western Europe and the continental one of eastern Europe. Major agents of the general atmospheric circulation pattern contributing to the maritime character of the climate are the Icelandic low-pressure system, the Azores high-pressure system and often the Asian (or Siberian) high-pressure system. The first two of them furnish western Europe with moisture-loaded air masses propelled by dominant westerly winds. Other major factors are: (1) the maritime influence of the Atlantic Ocean adding to climate 'oceanicity'; (2) the mountain ranges hindering the southward advance of maritime air masses and, thus, adding to climate 'continentality', and (3) the altitude effects in highland regions. Therefore, in general, the oceanicity of climate increases to the north and the west whereas the continentality increases to the south and east. During winter time, the air temperature isotherms run from north to south with values increasing westward, and in summer the isotherms run generally parallel to latitudes (from west to east) with temperatures increasing southward. The mean annual temperature thus decreases generally from north-west to south-east and the annual precipitation from west to east (Fig. 2.1) Table 2.1 summarises the mean climatic conditions over the area of Germany based on data from the German Weather Service (Deutsche Wetterdienst – DWD) for the standard climatological period of 1961–1990. Mean annual air temperature for Germany is +8.4°C with July being the warmest month and January – the coldest. DWD data indicate a gentle increase of annual temperatures after 1988 when compared to the 30-year mean value. Mean annual precipitation for Germany is

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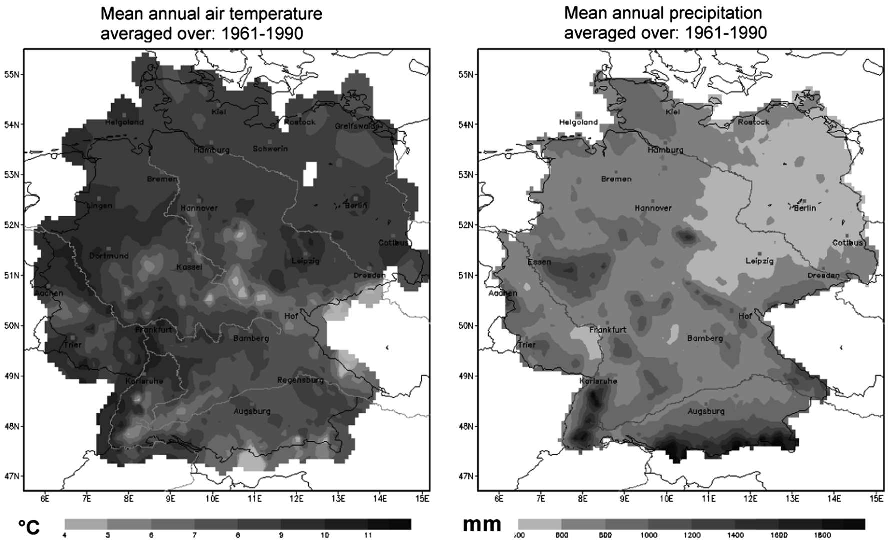

Fig. 2.1 Spatial distribution of mean annual T_a (°C, *left panel*) and mean annual precipitation amount (mm year^{-1}, *right panel*) in Germany. (Maps are derived from the Climate maps of Germany presented in www.klimadiagramme.de and are based on the data of the German Weather Service)

Table 2.1 Multiyear (1960–1990) monthly, seasonal and annual mean values and standard deviations (σ) of air temperature, T_a (°C) and precipitation rates, P (mm per period) averaged over the area of Germany (Mitchell et al. 2004). Season abbreviations: *MAM* March, April, May; *JJA* June, July, August; *SON* September, October, November; *DJF* December, January, February; *ANN* annual

	T_a	σ_T	P	σ_P
JAN	−0.5	2.9	50.8	19.5
FEB	0.4	2.7	40.5	19
MAR	3.7	2.1	47.9	17.7
APR	7.6	1.1	50.9	19.9
MAY	12.2	1.2	64.7	19.8
JUN	15.5	1	77.3	20.5
JUL	17.2	1.3	72	23.7
AUG	16.9	0.9	71.5	16.8
SEP	13.8	1.2	57.2	19.6
OCT	9.4	1.2	50.3	23.1
NOV	4.2	1.3	58.4	16.7
DEC	0.8	2.2	58.6	25.9
MAM	7.8	0.9	163.4	35
JJA	16.5	0.7	220.7	41.3
SON	9.1	0.7	165.9	32.2
DJF	0.2	2	149.9	69.7
ANN	8.4	0.7	699.9	92.8

700 mm with the pronounced seasonal peak in summer (June–August) with 31.4% of annual precipitation. Seasonal relative minimum value was observed for December–February – 21.5% of annual precipitation. Based on these climatic characteristics most of the land area in Germany could be considered as almost optimal for beech (*Fagus silvatica L.*) growth as beech prefers oceanic climates with at least 600 mm per year precipitation, with annual mean temperature of about +8° (though wide temperature variations are tolerated) and a growing season of at least 5 months (Mayer 1992). The climatic conditions in Germany fall around these mean values and are classified into four major climatic regions (Schüepp and Schirmer 1977), namely: (1) Northern Lowlands, (2) German Highlands, (3) The German Alpine Foreland and (4) The German Alps. Since the investigated sites are located within the German Highlands, a brief description of climatic conditions of this area is provided below.

The German Highlands belong to the Central European Uplands which start from the Massif Central in France and stretch to Poland and the Czech Republic. The Highlands are generally moderate in height with few peaks exceeding 1,100 m a.s.l. The area of German Highlands includes Saarland, Hessen and Thuringia, the north of Rhineland and the south of North Rhine Westphalia, the southernmost parts of Lower Saxony and Saxony Anhalt and western parts of Saxony.

In the Highlands, the climate continentality increases southward and eastward and well-pronounced orographic effects are observed. The influence of high-pressure systems gets stronger in this region especially during winter periods. The decrease of air temperature with altitude is well expressed in summer but is reduced in winter because of the stagnation of cold air in valleys enhanced by its radiative cooling. The moist Atlantic air masses are transported into this region by westerly winds so that western slopes receive more precipitation from orographic rain clouds than eastern slopes which are located in a rain shadow. Generally, the amount of precipitation at the same altitude decreases southward and eastward. Thus, two major factors that modify the climate at regional and local levels in the German Highlands are the height and the orientation of mountain ranges, and the variability of local topography (Schüepp and Schirmer 1977). The influence of topography on climatic conditions of the German Highlands, namely the increase of orographic precipitation and decrease of mean air temperature, is very well illustrated in the north by the Harz Mountains and Thuringian Forest. The mean air temperature at Bad Harzburg (300 m a.s.l) is 8.5°C and the mean annual precipitation is 813 mm, while at the highest point of the Harz Mountains, the Brocken (1,142 m a.s.l.), the mean annual air temperature is low (2.9°C) and the mean annual precipitation is high (1,594 mm) (www.klimadiagramme.de). The typical rain shadow area extends eastward of the Thuringian Forest with annual precipitation of less than 500 mm. The southern parts of the highlands, like the Bohemian Forest and Bavarian Forest belonging to the Bohemian Massif, receive the remaining Atlantic-originated moisture. At higher altitudes, an increase of total precipitation is accompanied by an increased share of snowfall.

2.2 Experimental Sites

The three investigation sites: Solling Mountains, Zierenberg and Göttinger Wald in Central Germany are quite similar in their topography and landscape features. They are situated in the south of Lower Saxony and in the north of Hessen, and being quite close together form a triangle with a side length of approximately 70 km. The sites are situated either on plateaus (Solling and Göttinger Wald) or on a slope (Zierenberg, see Chap. 1 "Site description") and are surrounded by forested rural areas. It should be emphasised that the weather data collected on these three sites significantly differ from standard synoptic and climate stations of the DWD as the meteorological stations of Solling Mountains, Zierenberg and Göttinger Wald are placed in the beech forest stands underneath tree canopies and not in open field surroundings as prescribed by the World Meteorological Organisation for its standardised meteorological stations.

2.2.1 Climatic Variables

To compare the microclimates of the three beech sites, three measured climate characteristics were chosen: (1) daily mean air temperature at 2 m above the surface organic layer (T_a); (2) precipitation amount at a nearby opening in the trees, and (3) daily mean forest soil temperature (T_s) at three different depths (5 cm, 10 cm and 20 cm – $T_{s,5}$, $T_{s,10}$ and $T_{s,20}$, respectively). Global radiation (sum of direct solar and diffuse sky radiation flux components in short wave spectral range from 300 to 3,000 nm) was measured at the Solling site only during the period from 1990 to 1999. For that reason, the 30-year mean values provided by DWD on sunshine duration and annual global radiation sums were used to characterise the energy input to beech ecosystems. The mean annual global radiation sums measured at Solling are used for partial validation of DWD data.

Air and soil temperatures were measured by means of a PT–100 resistance thermometer. The amount of precipitation was recorded using a Thies tipping bucket rain gauge (Adolf Thies, Göttingen, Germany) and a heated Hellmann rain gauge recorder. The global radiation was measured by means of a CM11 Kipp and Zonen pyranometer. The sensors were connected to Orion data loggers so that the measurements were performed automatically. The values were sampled with a 10-Hz frequency and averaged over 10 min at Göttinger Wald (e.g. Kreilein 1987) and over 15 min at Solling and Zierenberg.

Three time periods were chosen for calculating mean values: (1) annual; (2) the summer half-year period (May–October), which can be characterised as a period with foliage cover of deciduous forests and defined as the "growing season", and (3) the winter half-year period (November–April), which represents a leafless period or the "non-growing season". Thus, 'seasonal average' of a variable describes the mean values over 'growing' or 'non-growing' half-year periods. However, the limits of growth conditions of plants do not solely depend on monthly or seasonal average values of climatic variables. Extreme values of meteorological variables, their different combinations as well as the duration of stress conditions are also of great importance. The quantification of the damage on trees caused by weather extremes in terms of the tree vitality reduction still remains a challenging task and is a subject of numerous scientific discussions. The present article serves a descriptive purpose. It includes no detailed discussion on extreme values and their consequences but merely mentions the temperatures minima and maxima to give the reader some impression of the variability ranges at the study sites.

The measurements at the three beech sites were carried out from 1969 to 2002. However, not all parameters were measured continuously for the entire period. Air temperature was measured from 01.01.2001 to 31.12.2002 at the Zierenberg site, from 01.01.1990 to 31.12.1998 at the Göttinger Wald site, and from 01.01.1990 to 31.12.2002 at the Solling site. Any missing values for these stations were interpolated or extrapolated from the measured values at nearby DWD stations, e.g. from Kassel for Zierenberg, Silberborn or Holzminden for Solling, and Göttingen for Göttinger Wald, and thus are not independently derived.

2.3 Climatic Conditions at Beech Sites

Because of their location within the northern part of German Highlands, all three studied forest sites experience a smoothing maritime influence on air temperature variability through the mild and moisture-loaded Atlantic air masses which are transported by prevailing westerly and north-westerly winds. The additional effects of elevation and forest cover alter the microclimate of the measuring plots. The combination of various influencing factors results generally in mild air temperatures in summer and winter, high annual precipitation which exceeds potential and actual evapotranspiration rates, and the absence of a well-pronounced dry period. Fog occurs on about 70 days per year.

2.3.1 Solar Radiation

According to the climatological data of the 30 years 1961–1990, as provided by DWD (www.dwd.de), the sunshine duration in Germany ranges from 1,200 to 1,920 h $year^{-1}$ with the mean value of 1,542 $\pm$ 127 h $year^{-1}$. The mean values of sunshine duration within the area covering the experimental beech sites are well below the mean value for Germany (Table 2.2). The Solling and Zierenberg sites experience less sunshine than Göttinger Wald, The annual sums of global radiation on the three sites, however, differ only slightly whereas the insolation in the Göttinger Wald and Zierenberg sites is higher than in Solling. The results of global radiation measurements for Solling show an even lower value of annual radiation

Table 2.2 Mean annual sunshine duration (hours), radiation sums, GJ per year, (values in kWh per year m^{-2} are given in parenthesis) and the corresponding irradiances, W m^{-2}, (period 1961–1990) at Göttinger Wald (GW), Zierenberg (ZB), and Solling (SO). The mean annual radiation sums for the period of (1990–1999) measured at Solling (SO_{meas}) and correspondent mean irradiance are also shown

Site	Sunshine duration (hours)	Radiation sums	Irradiance (W m^{-2})
GW	1,400–1,450	3.4–3.5 GJ m^{-2} a^{-1}(960–980 kWh m^{-2} a^{-1})	109.6–111.9
ZB	1,300–1,350	3.4–3.5 GJ m^{-2} a^{-1}(960–980 kWh m^{-2} a^{-1})	109.6–111.9
SO	1,300–1,350	3.3–3.4 GJ m^{-2} a^{-1}(940–960 kWh m^{-2} a^{-1})	105–107.3
SO_{meas}	–	3.29 ± 0.24 GJ m^{-2} a^{-1} (915 ± 65.7 kWh m^{-2} a^{-1})	104.5

sum than that given by DWD. However, the difference is within the range of expected variability.

2.3.2 Air Temperature

The highest value of average annual air temperature, T_a, (Table 2.3) was observed at the lowest station – Göttinger Wald (420 m a.s.l.). However, the values of T_a observed at both Zierenberg (450 m a.s.l.) and Solling (504 m a.s.l.) sites are equal despite the 50 m difference in altitude. The T_a gradient between Göttinger Wald and Solling (80 m altitude difference), both of them located on plateaus, is about 0.6°C/100 m which is in a good agreement with annual averages observed at meteorological stations of the DWD. At the same time, the T_a value at Zierenberg which is on a slope is equal to that at Solling located 50 m higher on a plateau, indicating that besides the altitude effect local environmental and/or topographic factors are important for T_a gradients.

The annual courses of T_a are quite similar at the three sites, though their absolute values differ from one another. August is the warmest month at all sites (Table 2.3). This is rather untypical for the more continental climatic region of the German Highlands, where the maximum monthly T_a value usually occurs in July. It would be more characteristic for the Northern Lowlands with their stronger oceanicity. One of the factors causing the T_a maxima to occur in August is that the investigated forests are situated in the northernmost region of the German Highlands which forms a transition zone to the Northern Lowlands, having the cooling ocean influence in summer. Another factor may be related to the dense canopy of beech forests where the stations are installed. During the growing season, the canopy blocks the direct radiative heating of the underlying surface in the daytime and the radiative cooling at night, smoothing the daily amplitudes (Ellenberg 1996). The seasonal increasing of foliage density also slows down the spring to summer increase of the mean monthly T_a. Without the protective influence of foliage during winter, the T_a values are minimal corresponding to the expected values of the

Table 2.3 Mean T_a (°C) and precipitation rates (mm per year) for the observation period 1990–2002 averaged over: entire year, the growing season (May–October), and the non-growing season (November–April) at Göttinger Wald (GW), Zierenberg (ZB), and Solling (SO) (min and max values for the observation period in are parentheses)

Site	Air temperature			Precipitation		
	Annual	May–October	November–April	Annual	May–October	November–April
GW	7.4 ± 0.8 (5.5, 8.3)	12.6 ± 0.63 (11.3, 13.4)	2.2 ± 1.18 (−0.4, 3.7)	709 ± 193 (537, 973)	410 ± 156 (233, 596)	299 ± 143 (170, 453)
ZB	6.9 ± 0.72 (5.0, 7.7)	11.9 ± 0.59 (10.6, 12.6)	1.8 ± 1.0 (−0.6, 3.2)	754 ± 201 (535, 981)	406 ± 112 (281, 594)	348 ± 97 (237, 438)
SO	6.9 ± 0.75 (5.0, 7.7)	12.0 ± 0.67 (10.7, 12.8)	1.7 ± 1.01 (−0.8, 3.0)	1,193 ± 215 (8,621,571)	553 ± 254 (370, 915)	641 ± 238 (391, 896)

Table 2.4 Mean monthly temperatures (°C) and monthly precipitation rates (mm per month) for the period 1990 – 2002 at the Göttinger Wald, Zierenberg and Solling sites

Month	Göttinger Wald		Zierenberg		Solling	
	Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation
Jan	−0.3 ± 2.1	40 ± 28	−0.6 ± 1.9	53 ± 48	−0.8 ± 1.83	111 ± 102
Feb	0.8 ± 3.1	41 ± 158	0.5 ± 2.7	54 ± 50	0.3 ± 2.9	103 ± 88
Mar	3.5 ± 1.5	45 ± 19	3.0 ± 1.4	53 ± 31	2.7 ± 1.6	106 ± 194
Apr	6.7 ± 1.7	44 ± 31	6.1 ± 1.5	50 ± 70	6.0 ± 1.4	72 ± 78
May	11.3 ± 1.6	60 ± 69	10.6 ± 1.6	62 ± 51	10.7 ± 1.9	66 ± 70
Jun	13.5 ± 1.1	65 ± 26	12.7 ± 1.2	70 ± 67	12.7 ± 1.4	81 ± 40
Jul	15.6 ± 1.7	79 ± 68	14.9 ± 1.8	81 ± 44	15.2 ± 2.1	104 ± 87
Aug	16.1 ± 1.3	69 ± 56	15.2 ± 1.2	61 ± 85	15.5 ± 1.3	82 ± 50
Sep	11.6 ± 1.5	70 ± 45	10.9 ± 1.5	69 ± 54	11.0 ± 1.8	107 ± 101
Oct	7.6 ± 1.7	67 ± 53	7.0 ± 1.7	63 ± 41	7.1 ± 2.1	113 ± 63
Nov	2.8 ± 1.7	67 ± 66	2.5 ± 1.6	69 ± 65	2.6 ± 1.7	116 ± 104
Dec	−0.2 ± 2.2	61 ± 59	−0.4 ± 1.8	69 ± 71	−0.5 ± 1.8	133 ± 101

climatic region of the German Highlands. Average air temperatures in December and January are below 0°C with January as the multiyear average – the coldest month at all sites (Table 2.4). At all stations, the minimum temperatures in winter were about −11°C (±4°C) and the maximum temperatures in summer were on average around +22°C (±1.5°C). The absolute minimum for the observation period was as low as −20.6°C in Göttinger Wald and was recorded on 01.01.1997. At Solling and Zierenberg, the lowest air temperatures were recorded on 31.12.1978 as −18.6°C (Solling) and −17.5°C (Zierenberg). The warmest day at all stations was 09.08.1992 when the air temperature reached 27.8°C at Göttinger Wald, 27.5°C at Solling and 25.9°C at Zierenberg.

Multiyear average values for seasonal (growing/non-growing seasons) patterns of T_a at three studied sites (Table 2.3) show Göttinger Wald with the highest mean temperatures for all seasons. Mean values at Zierenberg and at Solling are equal to each other and lower than at Göttinger Wald. Similar differences are observed for seasonal maxima and minima values of T_a. At all stations, the amplitudes of inter-annual courses are higher for the non-growing season than for the growing one suggesting the highest variability of winter conditions from year to year. The T_a values at the Göttinger Wald site show the highest among the stations' amplitudes (4.1°C) of inter-annual course of values for the non-growing season. The temperatures of both the other stations had amplitudes of 3.8°C. The discussion on the inter-annual variability and its causes is outside the scope of this chapter.

2.3.3 Precipitation

The annual and seasonal mean values of precipitation for the three sites are given in Table 2.3. The annual mean rainfall is highest at Solling, which is about 1.5 times higher than at both Zierenberg and Göttinger Wald. The values presented in Table 2.3 indicate that Göttinger Wald is the warmest and driest of all three sites, which is probably related to its highest values for annual sunshine duration and radiation sums among the three stations. Highest precipitation at the Solling site is related to its location: the Solling ranges are the first massive obstacle for the dominant westerly winds from the North Atlantic and the North Sea. As described in Section 2.1, these westerlies usually bring moisture-laden air masses with high relative humidity and, therefore, with a big chance for cloud and precipitation formation when the air is orographically uplifted. The contribution of orographically-induced precipitation is significantly lower at the Zierenberg and Göttinger Wald sites because they are located leeward, i.e. in a rain shadow of the Solling Mountains. Being located on lower and narrower ranges than Solling, their own ability to block and lift the on-flowing air masses is weak.

The orography has also a significant effect on seasonal distribution of precipitation (Table 2.3). For example, the major part of annual precipitation at Göttinger Wald and Zierenberg (ca. 58% of annual values at Göttinger Wald and 54% at Zierenberg) occurs during the growing season, whereas at Solling most of the precipitation occurs during the non-growing season (53.5%). Mean annual courses of precipitation at the three sites follow generally the patterns of stations in the German Highlands (www.klimadiagramme.de) for the periods 1961–1990 and 1971–2000 (Table 2.4): namely, the two main maxima occur in midsummer and in midwinter and a local maximum in March. The midwinter maximum is rather weakly expressed at both Göttinger Wald and Zierenberg. The midsummer maximum at all three beech sites is shifted to July as against June for the DWD stations. Amount of precipitation at the Solling site during the non-growing season has a clearly expressed pattern of a monotonous increase from October to December and then a decrease until March. This pattern is typical for highland stations like Braunlage and Clausthal-Zellerfeld. Thus, at Solling, a pronounced precipitation peak occurs in December. About 15–20% of the annual precipitation at Solling site falls as snow. A continuous snow cover during winter periods seldom occurs, as the intermediate warm weather events often cause a thaw. The spring rainfall minimum in April, typical of highlands in general, occurs at all three forest sites, and extends to May at Solling. The secondary precipitation maximum in December–January is not clearly expressed at the Göttinger Wald and Zierenberg sites. This maximum is characteristic for all low-altitude stations of the Northern Lowlands and the northern part of the German Highlands and is strongly positively correlated to cyclonic activity of the North Atlantic Oscillation (NAO) (Wibig 1999). Thus, the precipitation courses result from the combined influence of orography and of atmospheric circulation patterns described in Section 2.1. During the summer months of June–August, convective precipitation prevails, with similar contributions at all three forest sites though the orographic effect causes higher absolute values at Solling. Summer monthly precipitation at Göttinger Wald and Zierenberg range between 60 and 80 mm month^{-1} and at Solling between 80 and 100 mm month^{-1}.

2.3.4 Variations of Air Temperature and Precipitation During the Observation Period

Annual mean values of air temperature, T_a, and the precipitation rates are shown (Fig. 2.2) for the entire observation period at the Solling site, because continuous measurements were carried out over the entire 33-year period only at this site. Both T_a and precipitation increased slowly from 1969 until 2002. This increasing trend becomes more evident in the patterns of 5-year running means of T_a and precipitation (Fig. 2.2). The patterns of both air temperature and precipitation for the observation period are almost sinusoidal with two clearly marked periods. According to running mean values the air temperature increased by 1.4°C and precipitation increased by 230 mm from the beginning of the 1970s to the end of the 1990s, i.e. the climatic conditions have become warmer and more pluvious. Running mean curves indicate that oscillations of air temperature and precipitation were running in reversed phases. The oscillations were correlated with the NAO index and especially with the winter index (as defined by Hurrell and van Loon 1997), positively for T_a and negatively for precipitation. This result is not unexpected as the positive phases of the NAO have often been associated with positive temperature anomalies and below-average precipitation over southern and central Europe (e.g. Hurrell 1995). The influence of the NAO is more pronounced in wintertime (Mareş et al. 2002). The amplitude of T_a oscillations increased with time toward 2002 and the variations of precipitation (Fig. 2.2) decreased. The minimal variation, i.e. the period with more or less constant, though high (around 1,000 mm year^{-1}), value of annual precipitation was observed during 1981–1994.

Values of T_a and precipitation are averaged over three unequal sub-periods, namely 1969–1980, 1981–1989 and 1990–2002, and the results are presented in Table 2.5. The table also contains the mean values for the entire period of 33 years

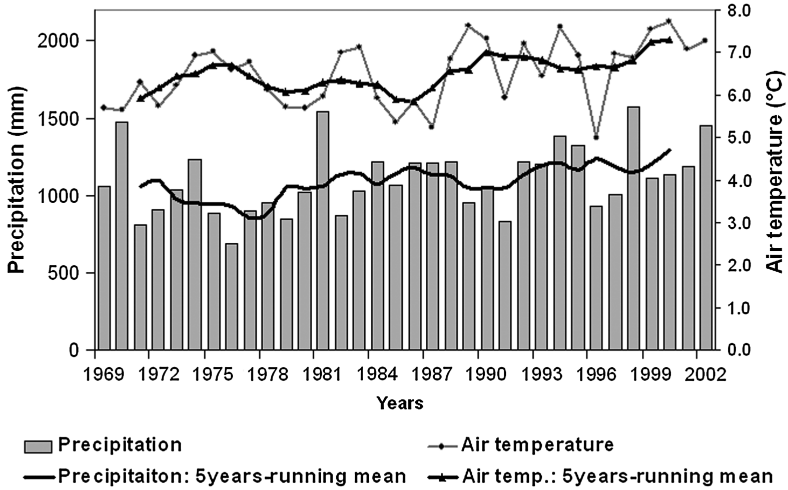

Fig. 2.2 The inter-annual variability of T_a and precipitation are shown for the Solling site. Running means of 5-year periods for air temperature and for precipitation are also shown

Table 2.5 Mean annual air temperatures (°C, 2 m above ground) and annual precipitation rates (mm year^{-1}) at the Solling site from 1969–2002 for the entire year, the growing (May–October), and the non-growing season (November–April) (min, max and amplitude values for corresponding periods in are parentheses)

Period	Air temperature			Precipitation		
	Annual	May–October	November–April	Annual	May–October	November–April
1969–2002	6.5 (5.0, 7.7, 2.7)	11.7 (10.2, 12.8, 2.6)	1.2 (−0.8, 3.4, 4.2)	1,095 (6, 72, 1,571, 899)	524 (276, 915, 639)	571 (391, 896, 505)
1969–1980	6.2 (5.7, 7.0, 2.7)	11.4 (10.2, 12.5, 2.3)	1.0 (−0.7, 3.4, 4.1)	951 (672, 1,440, 768)	487 (276, 681, 405)	464 (396, 759, 363)
1981–1989	6.3 (5.2, 7.6, 2.4)	11.7 (10.8, 12.8, 2.0)	0.8 (−0.7, 2.7, 3.4)	1,146 (878, 1,527, 649)	532 (379, 744, 365)	613 (450, 800, 350)
1990–2002	6.9 (5.0, 7.7, 2.7)	12.0 (10.7, 12.8, 2.1)	1.7 (−0.8, 3.0, 3.8)	1,193 (862, 1,571, 709)	553 (370, 915, 545)	641 (391, 896, 505)

from 1969 to 2002, and the seasonal means of growing and non-growing seasons to describe forest growth conditions. The results show that the annual mean air temperature for the first two decades remained quite constant, but increased considerably (by 0.6°C) during the third decade (1990 – 2002). The T_a for the growing season showed a steady increase throughout the entire observation period with a total increment of 0.6°C. However, the mean T_a for the non-growing season decreased slightly (0.2°C) from the 1970s to the 1980s and then dramatically rose by 0.9°C during the 1990s. The amplitudes in mean *annual* T_a (calculated as period's maximal minus period's minimal values of annual temperature) for the sub-periods showed an increase of variability during the observation period. However, the amplitudes for *seasonal* mean T_a showed a weak minimum in the 1980s for both growing and non-growing seasons, i.e. a decrease by 0.3°C since the 1970s and then a slight increase by 0.1°C to the 1990s. It should be noted, however, that during the period of 1981–1989 two major warm ENSO events of 1982 and 1988 considerably altered the pattern of general atmospheric circulation.

The annual precipitation during the observation period increased continuously from 1969–1980 to 1990–2002 with a total increment of 242 mm year^{-1} which was mainly due to an increase in precipitation during the non-growing season, especially during the 1980s (Table 2.3). November–April precipitation increased by 149 mm year^{-1} whereas the May–October values increased by only 45 mm year^{-1}. The increase of annual and seasonal precipitation from the 1980s to the 1990s was notably less: 28 mm year^{-1} for the non-growing season and 21 mm year^{-1} for the growing season.

This general increase in precipitation for the winter months could be explained by changes of the atmospheric circulation pattern over Europe during the period of 1960–1990. Zonal flow (westerlies) was generally strengthened, especially during winter periods. The rise of anti-cyclonic activity, however, has slowed down the precipitation increase during the last decade (Kyselý and Huth 2006).

The period of 1969–1980 was somewhat abnormal for the Solling forest site as the pattern of seasonal distribution of precipitation was reversed – more than half of the annual precipitation (51%) occurred in the growing season. A possible reason could be the decrease in frequency of the 'north' types of atmospheric circulation over Europe in winter (prevailing northern flows) and their increase in summer during the decade (Kyselý and Huth 2006). Table 2.5 also illustrates the fact that the decadal amplitudes (maximum minus minimum annual precipitation for a decade) during the 33-year period were always higher for growing seasons than for non-growing ones. The values point to a reduction of intra-decadal variability during the 1980s whereas the amplitudes increased further in the 1990s.

2.3.5 *Soil Temperature*

The annual mean values of soil temperature at three depths ($T_{s,5}$, $T_{s,10}$, $T_{s,20}$,) are presented in Table 2.6. Changes in soil temperatures at the investigated sites did not always follow the pattern of air temperatures. The Solling station is the 'coldest' site.

Table 2.6 Mean daily soil temperatures (°C) at 5, 10 and 20 cm depths at the Zirenberg, Göttinger Wald and Solling sites (1998–2002) (min, max and amplitude values in parentheses)

Depth	Soil temperature		
	Göttinger Wald	Zierenberg	Solling
5	7.2 ± 4.33 (−3.9, 17.7, 21.6)	8.4 ± 4.27 (1.3, 17.0, 15.7)	6.0 ± 4.02 (−2.5, 16.2, 18.7)
10	7.0 ± 4.18 (−3.4, 16.9, 20.3)	8.2 ± 4.19 (1.3, 16.4, 15.1)	6.0 ± 3.94 (−2.2, 15.8, 18.0)
20	7.1 ± 3.93 (−2.5, 16.1, 18.6)	8.2 ± 4.15 (1.4, 16.0, 14.6)	6.4 ± 3.75 (−0.5, 13.0, 13.5)

However, the warmest one is not Göttinger Wald but Zierenberg despite its higher altitude and the north-east exposure of the slope. The Göttinger Wald station almost exactly represents the transition state, but also shows the highest T_s variability during the observation period. Temperature amplitudes (differences between maximal and minimal values are given in parentheses in the table) in all three soil layers at the Göttinger Wald site exceeded 18.5°C reaching 21.6°C at 5 cm depth, while at the Zierenberg site all amplitudes were smaller than 16°C. Highest amplitude at the Solling site was 18.7°C in 5 cm depth.

Seasonal variations of temperatures at different soil layers ($T_{s,5}$, $T_{s,10}$, $T_{s,20}$) were not in phase with the variations of T_a. The largest variability and the highest amplitude of the temperature variation are expected at the surface of bare soil and this temporal variability should decrease with soil depth (e.g. Scharringa 1976). In a forest, the variability should be smoother even at the soil surface because the forest canopy reduces the short-wave solar radiation input to and the thermal radiation loss from the surface organic layer as compared to the open field. A general decrease of variability with depth was also illustrated by a decrease in the period of amplitudes presented in Table 2.4. In Fig. 2.3, the seasonal variations of the vertical profiles of the soil temperature at the three sites are shown. As expected, the highest temperatures ($T_{s,5}$, $T_{s,10}$, $T_{s,20}$) at all sites were observed during the summer months, before the cooling period followed in the autumn. The spring mean temperatures at all depths were considerably lower than the autumn ones and followed the same pattern as T_a values.

Generally, with increasing solar and thermal radiation input to the soil surface, the upper soil surface is warmed up first, then the temperatures of the deeper soil layers follow. Therefore, in summer when the soil surface receives an increasing amount of energy from the sun and from the atmosphere, its energy balance becomes positive and soil temperature decreases with depth. During the winter season, when the incoming short-wave solar radiation is low in the temperate climate zone, the soil surface energy balance is usually negative and thus the temperature increases with soil depth. During the transition periods of spring and autumn when the short-wave radiative heating and long-wave cooling are almost balanced, the soil conditions could be considered as isothermal (Fig. 2.3). This ideal temporal pattern of soil temperature profiles holds true at the Göttinger Wald site but not at the Zierenberg and Solling sites. At Zierenberg, the mean seasonal $T_{s,5}$

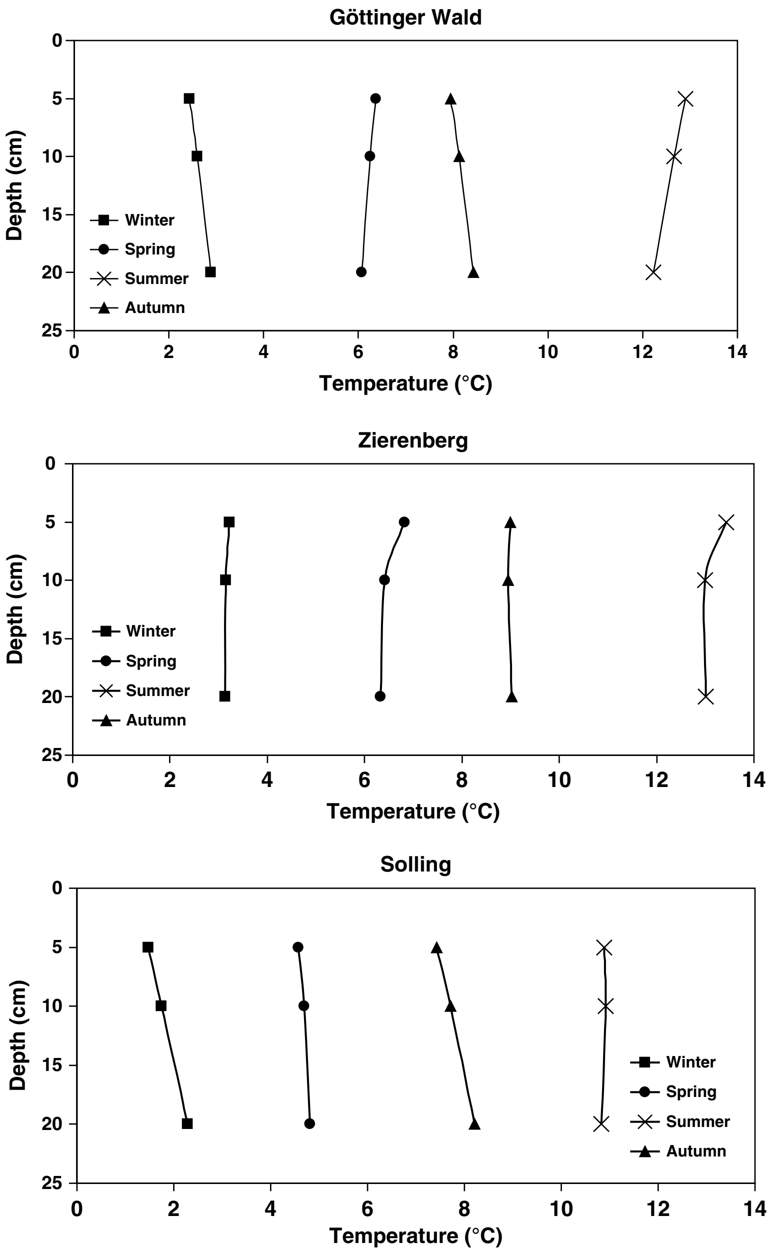

Fig. 2.3 Means for different seasons of vertical profiles of soil temperature at three different beech forest sites are given for the period 1990–2002: Göttinger Wald (*upper panel*), Zierenberg (*middle panel*) and Solling (*lower panel*)

Table 2.7 Vertical gradients of mean seasonal soil temperatures (°C m^{-1}) between the layers of 0.05 m and 0.20 m at sites Zirenberg (ZB), Göttinger Wald (GW) and Solling (SO) (1998–2002)

	Vertical gradients			
Site	Winter	Spring	Summer	Autumn
GW	3.1	2.0	−4.5	3.1
ZB	−0.6	−3.3	−2.9	0.26
SO	5.5	1.6	−0.04	5.2

were always slightly higher (from 0.4°C in summer to 0.04°C in autumn) than in the deeper layers ($T_{s,10}$ and $T_{s,20}$). At the Solling site, in contrast, the upper soil layers were colder than lower ones during all seasons except summer. The higher mean T_s values in the upper soil layers were also observed by Holst et al. (2000) in intensively thinned beech stands growing on north-east slopes, while the unmanaged control stand showed a temperature increase with depth or at least an isothermal vertical profile. This influence of forest structure was confirmed by the fact that the Zierenberg stand had a considerably lower stem density than the Solling and especially Göttinger Wald stands (see Chap. 1).

The absolute values of vertical gradients of soil temperature between $T_{s,5}$ and $T_{s,20}$ varied differently at all stations (Table 2.7). While at the Solling site the highest gradients of approximately the same magnitude were observed during autumn and winter, the maximal values at the Zierenberg site occurred in spring and summer and the lowest values in autumn and winter. At the Göttinger Wald site, the highest gradient was observed in summer, as also at the Zierenberg site, but the lowest in spring. The annual gradient was also the highest at the Solling site as well (2.96°C m^{-1}, directed upward) and the lowest at the Göttinger Wald site (−0.08°C m^{-1}).

2.4 Comparison with Other Climatic Regions

The three investigated beech sites, Göttinger Wald, Solling and Zierenberg, are located in the climatic region of the German Highlands (Central Germany). In order to position the climate conditions of these sites against the general climatic situation in Germany the beech stations are plotted within the Precipitation-T_a space (Fig. 2.4) based on the 30-year mean values of DWD. The figure also shows that the mean air temperature at all three studied beech stations was slightly lower than the average for Germany (8.1 ± 1.3°C). The same holds true for the annual precipitation rates at the Göttinger Wald and Zierenberg sites which were lower than average for Germany (700 ± 237 mm $year^{-1}$). The annual precipitation rate at the Solling site was among the highest in Germany exceeding the mean value by far.

To compare the growth conditions on the experimental sites with not only to the general climate in Germany but specifically to other beech sites growing in different German climatic regions, the air temperature (T_a), soil temperature ($T_{s,10}$) and precipitation values of five beech sites were compiled. These sites were located to the north, southeast, south and southwest of the studied ones. The northernmost station under the beech canopy at the Belauer forest about 30 km south of Kiel represents the Northern Lowlands. The southwest is represented by beech forests near Tuttlingen which is located in Schwabian Alb – a part of the Jura Mountains. To the southeast, the Bavarian Forest site Mitterfels is situated within the southern part of the German Highlands. A southern but not the southernmost site is the beech forest near Freising which is located at a slightly higher latitude than the Tuttlingen forests. All stands with the exception of the Belauer forest are highland forests, i.e. above 400 m a.s.l (Table 2.8). The observation periods varied from station to station which complicated a comparison, but it still provided sufficient information of a descriptive nature. To position these stations against the general climatic situation in Germany and against the three studied sites, the additional beech stations are also plotted within the Precipitation-T_a space at Fig. 2.4.

Annual mean T_a values in beech forests varied strongly in Germany with an amplitude of 2.9°C (Table 2.8). However the differences between forest stations were much lower than the absolute amplitude across Germany which was 8.8°C (Fig. 2.4) or even as high as 15.7°C if the Zugspitze station was included. It should also be noted that generally the mean T_a value averaged over the considered beech forests across Germany is below the ‘geographical’ mean value of T_a for Germany. Considering the dry potential temperature θ_d[1] to filter out the differences caused by different altitudes one can observe the expected latitudinal effects. θ_d increases from the northernmost station at Belauer to Central Germany and then to three southeast/southwest stations. The southern station at Freising shows an ‘intermediate’ θ_d value of 13°C though its latitude is within the range of the other southern stations. Thus, the elevation effects are not clearly expressed, although the highest station of Mitterfels has the lowest T_a value. Considering the absolute values of T_a at all beech forest stations (Table 2.8), the three studied beech forest sites are close to the average value, but are somewhat ‘colder’ than all other stations (even those at higher altitudes) except the one at Mitterfels.

The annual rainfall rates at the selected sites range between 700 mm and 1,600 mm with highest values at Solling and Mitterfels and the lowest at Göttinger Wald and generally exceed the actual evapotranspiration rates.

Pattern of soil temperature values ($T_{s,10}$) does not fully correspond to the pattern of air temperature. The values of $T_{s,10}$ depend upon many factors such as inclination and orientation of slopes, the density of tree canopy which controls the transmission of solar and thermal radiation to and from the soil surface, the temperature conductivity of the litter and soil layers above the temperature sensor, the litterfall rate changing the depth of the sensor with time, and the heat flow from the layers under the temperature sensor. The highest altitude site, Mitterfels, showed $T_{s,10}$

[1]The dry potential temperature of air parcel at pressure P is the temperature that the parcel would acquire if dry adiabatically brought to a standard reference pressure P_0 (e.g. at sea level). It is denoted as θ_d and is often roughly calculated assuming 1°C per 100 m altitude

Table 2.8 Comparison of air temperature (°C, 2 m above the ground, except at Tuttlingen at 1.5 m), dry potential temperature, soil temperature at 10 cm depth (°C), precipitation (mm year^{-1}), in beech forests at different sites across Germany (from north to south)

Site name	Coordinates	Altitude	Time period	Air temp.	Dry potential temp.	$T_{s,10}$	Precipitation
Belauer Forst	54°6′N, 10°16′E	50 m	1989–1998	7.3	7.7	7.1	769
Solling	51°46′N, 09°34′E	504 m	1990–2002	6.9	11.8	6.1	1,193
Göttinger Wald	51°32′N, 10°03′E	420 m	1990–2002	7.4	11.6	7.0	709
Zierenberg	51°22′N, 09°16′E	450 m	1990–2002	6.9	11.3	8.2	754
Freising	48°2′N, 11°4′E	508 m	1998–2005	8.1	13.1	8.8	840
Mitterfels (Bayerischer Wald)	48°6′N, 12°4′E	1,025 m	1998–2005	5.2	15.2	6.5	1,598
Tuttlingen (NE)	47°59′N, 8°45′E	800 m	2000–2004	7.5	15.4	7.6	783
Tuttlingen (SW)	47°59′N, 8°45′E	800 m	2000–2004	7.9	15.7	8.6	800
Mean of all stations				7.15 ± 0.89	12.7 ± 2.7	7.5 ± 0.98	931 ± 309.5

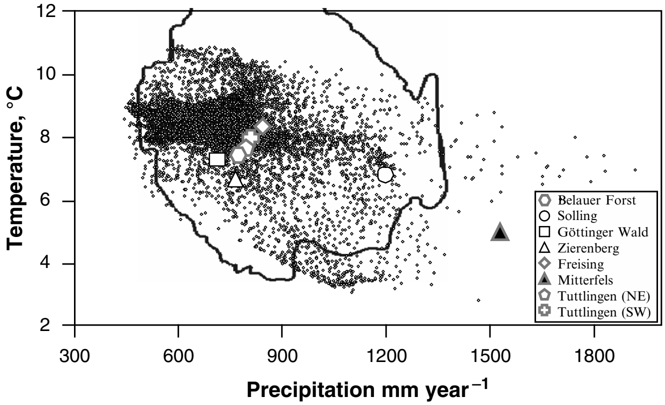

Fig. 2.4 Mean annual T_a (°C) versus mean annual precipitation sums (mm year^{-1}) (data of the German Weather Service, DWD) over Germany. The *geometrical symbols* denote the stations in beech forest as given in Table 2.1. The *solid black line* denotes the 'climate envelope' (Klimahülle) of beech according to Kölling and Zimmermann (2007)

values below the mean but not the lowest $T_{s,10}$ value of all sites. The lowest value was observed at Solling and the highest at Freising, while Tuttlingen (north-east) was very close to the mean value over all stations. The $T_{s,10}$ values for the Göttinger Wald and Zierenberg sites differed strongly from the mean, where the first one was considerably below and the latter one considerably above the mean $T_{s,10}$ value of all the stations.

Figure 2.4 shows that most beech stands in Germany lie within the 'climate envelope' of beech as defined by Kölling and Zimmermann (2007). The considered stations are not exactly but very close to the centre of this climatic envelope or optimum (Mayer 1992), where the competition strength of beech has to be the strongest. The exceptions are the beech sites in Germany, located at high altitudes, such as the highland beech stand at Mittelfels in the Bayerischer Wald (1,025 m), which fall outside the climate envelope of beech. Growth on such sites may be limited due to severe climatic conditions. Still, they are inside the critical limitations for *F. sylvatica* given by Manthey et al. (2007) with the lower limit: 471 mm year^{-1} and the upper limit: 2,000 mm year^{-1}. The Solling, which has the almost optimal air temperature, but lowest mean soil temperature of all the considered beech forests, is still well within the envelope, though the amount of precipitation puts it close to the limits of the envelope. The site of Freising appears to be the most optimal one with both $T_{s,10}$ and T_a above +8°C and with annual precipitation above 840 mm year^{-1}.

2.5 Conclusions

The climatic conditions of three beech sites from the German Highlands, Solling, Zierenberg and Göttinger Wald, are described. It is shown that Göttinger Wald is distinctly the warmest site of the three with a mean annual air temperature of 7.4°C and with the highest absolute amplitude for the period of observation. Zierenberg, however, is the warmest in terms of soil temperature (8.2°C). Solling has the highest annual precipitation (1,193 mm), whereas other forests are drier (around 700 mm), being in the rain shadow of the Solling mountains.

All the three studied stands are to some extent untypical for the German Highlands because the warmest month there is not July but August, which is due to oceanic influence and the effect of vegetation cover. January is the coldest month at these sites.

There is a clear evidence of an increase of air temperature and annual precipitation during the 33-year period of observations at the Solling site. However, the increase of total annual precipitation was mainly due to the increase of precipitation during the non-growing ('winter') season.

Changes in climate will have significant effects on forest ecosystems, as discussed by Gravenhorst (1993). However, the present values of climatic variables at the eight beech forests representing all main climate regions of Germany and including the three study sites in Central Germany are quite close to the optimum for the growth of beech. However, the Solling Forest is close to the limits of the beech climate envelope in terms of precipitation values, and the projected increase of winter precipitation under climate change may move it outside the envelope. The climatic conditions of Göttinger Wald and Zierenberg are sufficiently close to the average values for Germany, and therefore may be considered as representative of present conditions of beech forest growth in Germany.

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