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Twenty Years of Heat and Water Balance Climatology
at the Hartheim Pine Forest, Germany

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Abstract

The Hartheim pine forest is an ecosystem in the dry region of the southern upper Rhine valley in Germany. A project “Monitoring the Hartheim pine forest” was initiated in 1973 and is continuing. One of its objectives is to provide long-term measurements of the net radiation and its components, to calculate the energy fluxes and other hydrological parameters.

Sufficient studies on the climatology of the ‘primitive’ elements of climate exist in central Europe. But long-term series of measurements of the physical processes controlling these elements above different characteristic surface types are missing. The study of heat balance monographies (e.g. Budyko, 1974; Miller, 1981; Kessler, 1985; Hantel, 1989; Baumgartner, 1990) illustrates this deficit drastically. An aspect of our investigations is to study the long-term behaviour of the above-mentioned complex physical variables in relation to weather and climate. Furthermore, we examine whether it is possible to distinguish between the changes, for example, of the ratio of net radiation to global radiation caused by the dynamics of climate and the changes caused by alterations of the ecosystem. Natural and human influences on the pine stand at Hartheim led to an 8-m growth in height during the monitoring period.

We present some examples showing that the dynamics of the weather hide other effects within the frame of 20 years of measurements. On the other hand, evident changes in interception and transpiration are due to a changing forest ecosystem.

Keywords: Long-term series of measurements; Heat balance climatology; Radiation and energy budget; Water balance; Pine forest; *Pinus sylvestris*

1. Introduction

The Department of Meteorology at Freiburg University has been managing a climatological research site in a pine forest situated in the southern Rhine valley plain since the beginning of the 70s. One of the aims there is to investigate the long-term behaviour of the components of net radiation, the components of the energy balance and the terms of the water balance equation in this growing forest.

2. Site description

The experimental site is located in the lower part of the upper Rhine valley near the village of Hartheim 20 km south-west of Freiburg (Jaeger, 1978; Kessler et al., 1979; Schott, 1980; Merkel, 1987; Kessler and Jaeger, 1994); see Figs. 1 and 2. Geographical coordinates are 47°56'N, 7°37'E; the altitude is 201 m above sea level. The area is a highly uniform flood plain. The approximate dimensions of the forest are 10000 m (N–S) by 1500 m (W–E). Using a tower height-to-fetch relationship of 1:100, the site has sufficient fetch in all wind directions. The main wind

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direction is SSW. Due to some river regulation in the past and the sealed Rhine bypass channel the groundwater table has dropped to 7 m below the surface. Groundwater uptake by the trees is not possible. On the other hand percolation from the surface to groundwater is negligible (Schäfer, 1977; Hädrich, 1979).

The site is considered to be an ideal place to carry out radiation measurements. The view of the horizon is reduced by values of just less than 3° .

In 1996 the trees (*Pinus sylvestris*) were 37 years old. After the construction of the Rhine bypass channel the original riparian forest died. So the forest administration decided to install a pine plantation

Fig. 1. Picture of the Hartheim pine stand with its 30 m high measuring tower.

Fig. 2. Map of the surroundings of the Hartheim site.

after a complete deep ploughing. Fig. 3 presents the development of the pine stand. The mean stand height more than tripled from the beginning of the monitoring up to now. The best investigated biometrical data set at the Hartheim site consists of the mean stand heights (Fig. 3). It is the only homogeneous data set available to characterize the development of the stand. Eight pilot trees have been measured twice a year yielding the mean stand height. The forest management carried out three thinnings in the years 1970/1971, 1981/1982 and 1991/1992. The resulting stand density reductions are indicated by means of the solid line in Fig. 3.

Fig. 3. Stand development at the Hartheim site.

At the first thinning, 1970/1971, every third row of the pine plantation was removed. The following thinnings can be characterized as light-ground thinnings (1981/1982 and 1991/1992). Here the over-topped trees in the surroundings of the dominant elite trees (final crop trees) were cut. The maximum difference in height between the suppressed and the dominant trees is about 1 m.

We can detect the impact of the forest management in the growth of the trees. The dry period at the end of the 80s reduced the growth in height. Some dendroclimatological investigations at Hartheim forest demonstrate that precipitation conditions limit the growth and yield of forests in the southern part of the upper Rhine valley plain (Merkel, 1987).

In 1992 further biometrical stand parameters in the close surroundings of the towers were determined (Jaeger and Kessler, 1996):

Mean diameter of the trees at breast height: 0.11 m (range 0.05–0.23)

Cumulative circumference at breast height: 1320 m ha⁻¹

Cumulative basal area: 38 m² ha⁻¹

Sapwood area: 26 m² ha⁻¹

Total projected leaf area index L : 2.8 m² m⁻² (determined by means of a biomass harvest of five trees)

Fig. 4. Schematic representation of the experimental site at Hartheim and the location of the sensors. On the left: situation from September 1977 until summer 1985; on the right: present experimental design.

Canopy closure: ca. 85%

Canopy storage capacity: 1.53 mm (calculated by means of 34 precipitation events from 1978 to 1985; Kessler et al., 1988)

Fig. 4 shows the development of the towers which have been used during our investigations. The towers grew, so to speak, in step with the trees as we raised the measuring levels to match them (Jaeger et al., 1986). Only the measuring height of 9.6 m was fixed over the whole period for climatological reasons. The radiation sensors are exposed always ca. 2 m above canopy. The current arrangement of the sensors is also shown in Fig. 4.

The data recording was carried out by means of stripchart recorders in the first years. Two generations of process computers followed (Jaeger, 1980). Now the data are collected by means of data loggers.

3. The radiation

The net radiation R_n and its components have been measured by means of pyranometers (solarimeters) and by means of Schulze–Däke type net radiometers. An international comparison of net radiometers (Halldin and Lindroth, 1992) pointed out the advantages of the Schulze–Däke radiometer. All the radiation data reported here are related to the World Radiometric Reference (WRR, 1981).

Let us first consider the yearly pattern of the net radiation and its components (Fig. 5). $R_{s\downarrow}$ = total downward solar radiation or global radiation, $R_{s\uparrow}$ = reflected solar (global) radiation, $R_{l\downarrow}$ = downward atmospheric longwave radiation (counter radiation) and $R_{l\uparrow}$ = total of the upward terrestrial longwave thermal radiation and the atmospheric longwave radiation reflected at the canopy.

The values are mean values of every day of the year from 1974 to 1988. Note that this data set is completely unbroken (Kessler and Jaeger, 1994). All mean daily values were calculated from the individual daily totals of 15 years. The curve of the mean daily values was obtained by means of 11-day running means (low-pass filtering).

Two particular points should be noted: the decrease of the longwave radiation components $R_{l\downarrow}$ and $R_{l\uparrow}$ in February and the strong positive singularity of the global radiation $R_{s\downarrow}$ in April. Both

Fig. 5. Annual pattern of the components of the net radiation above Hartheim pine forest (1974–1988).

phenomena can be explained as a result of low mean cloudiness (see Fig. 6). Both Figs. 5 and 6 show that the values concerned exhibit a calmer pattern in autumn than in spring, as can also be observed in many elements of the climate in central Europe. The longwave radiation budget ($R_{l\downarrow} - R_{l\uparrow}$) is quasi constant (Fig. 5, not plotted especially), the maximum of this difference in April again being due to the cloudiness.

Fig. 6 deals with the cloudiness in the same way as the previous figure. R_{pot} = potential shortwave radiation (solar radiation on a horizontal surface unit in the absence of an atmosphere), CI = mean daily values of cloudiness, calculated from hourly values and $R_{s\downarrow}$ = total downward solar radiation.

Fig. 6. Annual pattern of the potential shortwave radiation (R_{pot}), the cloudiness (CI) and the shortwave incoming radiation ($R_{s\downarrow}$) at Hartheim (1974–1988).

Fig. 7. Radiation efficiencies at the Hartheim site, annual means from 1974 to 1988.

It is a lucky circumstance that we could use the hourly monitoring of the cloudiness from an airbase which was situated close to our site. Minimum cloudiness occurs in the summer season. The greater variability in this element of climate again occurs in springtime, as was pointed out earlier.

To introduce Fig. 7, we first show the equations which are the basis of the related calculations:

$$R_n = (R_{s↓} - R_{s↑}) + (R_{l↓} - R_{l↑})$$

$$R_n/R_{s↓} + R_{s↑}/R_{s↓} + (R_{l↑} - R_{l↓})/R_{s↓} = 1$$

where R_n = net radiation, $R_n/R_{s↓}$ = radiation efficiency, $R_{s↑}/R_{s↓}$ = shortwave albedo and $(R_{l↑} - R_{l↓})/R_{s↓}$ = longwave radiation budget normalized by means of the global radiation $R_{s↓}$.

The terms were calculated from measured yearly totals. The radiation efficiency is a surface specific property which depends on the reflection characteristics respectively and on the related energy exchange of the surface type considered. The highest efficiency values as well as the lowest (as far as vegetated surfaces are concerned) are achieved by forest surfaces, with the highest values above coniferous forests and the lowest observed above deciduous stands (Kessler, 1985).

The albedo is considered to be a more 'conservative' value in spite of the forest growth and the forest management. On the other hand, the $R_n/R_{s↓}$ ratio shows a tendency to reduce. This intensifies the $(R_{l↑} - R_{l↓})/R_{s↓}$ ratio because of the non-changing

albedo values. During the stand development, which was monitored for 15 years, we detected an alteration of the longwave radiation fluxes, related to the forcing function, i.e. downward solar radiation $R_{s↓}$. The reason for this is the changing canopy due to the growth of the forest, which controls all the energy fluxes. Moreover, the longwave downward radiation $R_{l↓}$ changed partly due to changes in the atmosphere close to the canopy. A detailed investigation in connection with the other energy budget terms is in preparation.

4. The energy balance

Now let us consider the components of the heat balance equation (Fig. 8). All the flux densities are defined as being positive if they transport energy to the reference level (outer active layer of the pine stand):

$$R_n + G + J + H + \lambda E = 0$$

where R_n = net radiation, G = soil heat flux, J = stand heat flux (rate of change in stored energy in the air layer of the stand and in the biomass), H = sensible heat flux and λE = latent heat flux.

Firstly we determined the totals of the individual months which were then aggregated to yearly totals. The monthly values were estimated as follows. The

Fig. 8. Mean yearly energy balance terms in Hartheim (1974–1991). R_n = net radiation, $(G + J)$ = heat storage in soil (G), stand air and biomass (J), H = sensible heat flux, λE = latent heat flux.

Fig. 9. Mean monthly soil heat flux G (accumulated) from 1973 to 1990.

net radiation R_n was measured, as described above. The soil heat flux G was computed on a hourly basis by means of a combination method. From the soil surface down to a depth of 20 cm we calculated the rate of change of the energy content in this layer using soil temperature measurements (-1 , -3 , -5 , -10 and -20 cm). At deeper levels we used the heat conduction equation (Jaeger and Kessler, 1996). Latent heat flux values λE on a monthly basis were calculated using the water balance equation (Kessler et al., 1988). Finally the sensible heat flux H was estimated as a residual of the energy balance equation.

Fluctuations of the net radiation R_n from year to year are first of all due to variations in cloudiness. A high net radiation R_n of the kind observed in 1976 was never again recorded later on. In spring and summer 1976 we observed only slight cloud cover. The latent heat flux λE is controlled by the precipi-

tation regime because percolation is negligible at the Hartheim site. On the other hand, as the groundwater table lies at a depth of 7 m below the surface the trees cannot use the groundwater for transpiration.

The energy residue led to the flux of sensible heat H . The curves of H and λE are running countercurrently in general. During the driest years, 1976, 1985 and 1991, the yearly totals of the sensible heat H exceeded the yearly totals of the latent heat λE . The storage term of soil, air and biomass ($G + J$) amounted practically to zero every year. The interannual variations of the heat balance terms are principally caused by weather noise. It is necessary to normalize the radiation terms by means of the global radiation (see above) and the evapotranspiration values by means of the precipitation input (see below) to discover the changes caused by the forest growth.

A distinct view of the energy processes in the soil (G) is presented in Fig. 9. The graph shows monthly

Fig. 10. Monthly averages of the hourly soil heat flux G (W m^{-2}) of May 1974 to May 1983 (from Garthe, 1985).

totals of the soil heat flux G summed up from 1973 to 1990. The yearly oscillation is very well documented. Concerning the long-term trend, we have to distinguish again between the weather forcing and the influences of the stand growth. The decrease of the curve until 1976 shows a slightly rising energy gain of the soil which is due to the strong opening up by means of the thinning of the years 1970/1971. Furthermore several dry years led to a greater warming of the soil. The gradient of the curve from 1976/1977 onwards is the result of the gradual shadowing of the forest floor caused by the canopy closing. The gradient of the curve is further flattened again through the thinning in 1981/1982 and through the increased warming of the soil during the dry years 1988 to 1990. Here a recurrent latent heat flux λE (Fig. 8) provided more energy favourable to the soil heat flux G .

The behaviour of the soil heat flux G , as controlled by the stand development, is also shown by the daily patterns of the months of May from 1974 to 1983 in Fig. 10 (from Garthe, 1985). During the first

years the sun was able to shine onto the forest floor. But continuous closing of the canopy cuts it off more and more. Thus, the amplitudes of the mean monthly patterns were flattened progressively. The thinning in 1981/1982 with its clearing of the canopy enabled the sunshine to reach the forest floor again and to affect the soil heat flux.

The accumulation curve of the storage term of the stand air and biomass J , which is likewise calculated from 1973 to 1990, shows another pattern (Fig. 11). The formally estimated declining tendency lies within a very small range. It shows nevertheless that the stand gains more and more energy due to the increase in biomass of the forest. The yearly variation is again very pronounced. It is unambiguously modified by the permanently changing weather situation which is typical in central Europe.

The mean yearly course of the daily totals of the storage term in the stand J is presented in Fig. 12. The stand gains energy from February to July. In contrast to this the sign of this heat flux is positive during the other months of the year. But it should be

Fig. 11. Accumulation curve of monthly means of the storage term in stand air and biomass J at Hartheim site (1973–1990).

Fig. 12. Monthly means of the daily totals of the storage term in the stand J (1974–1991).

pointed out that this heat flux is very small compared with the other heat budget components.

5. The parameters of the wind profile

If we want to determine the fluxes of sensible and latent heat above a forest canopy by means of the aerodynamic profile method we need the wind profile parameters with roughness length z_0 and zero-plane displacement d .

In our view the foremost question here is how these parameters are related to the stand development and the variability of the weather. The problems of the wind profile measurements at Hartheim forest are described by Vogt and Jaeger (1990). The question is answered by means of a data set beginning in 1985 (Fig. 13) which is based on measurements at the big tower (Fig. 4). Wind was measured at the following heights: 12.12 m, 15.47 m, 19.11 m, 23.57 m and 29.60 m.

To estimate the wind profile parameters we firstly determined the hours of neutral atmospheric stratification by means of the local Richardson number (Lettau, 1958). During these hours friction velocity u^* , zero-plane displacement d and roughness length z_0 in the adiabatic surface layer of the atmosphere were calculated according to a procedure given by Robinson (1961).

Schott (1980) found z_0 to increase and d to

become smaller with growing wind speed values using 1975 data. Vogt and Jaeger (1990) confirm these results. Fig. 13 shows monthly mean values from 1985 to 1991. During this period no forest management activities were carried out. The gap in 1989 results from destruction of the electronics by a flash of lightning. The unsteadiness between the data before and after the lightning event is due to the installation of new cup anemometers.

Leaving out of consideration the inhomogeneity of the time series described above, Fig. 13 shows the following features:

1. The zeroplane displacement d is increasing in line with the growth in height of the trees as expected (see Figs. 3 and 13).
2. The roughness length z_0 undulates to a relatively stable degree at between 1 and 2 m.
3. The variability of the two parameters d and z_0 is due to the wind fluctuations from month to month caused by the weather. This is expressed particularly clearly by the countercurrent behaviour of the two curves.

Fig. 13. Mean monthly zero plane displacements d (dots) and roughness lengths z_0 (open circles) (1985–1991).

6. The hydrological conditions

Fig. 14 is a presentation of the mean monthly water storage in the soil together with the mean monthly totals of precipitation P and evapotranspiration E at the Hartheim site. The period of the mean value calculation is 1974 to 1991. Until 1980 the soil water content was determined weekly by means of a neutron probe. From 1981 onwards we performed a gravimetric determination every fortnight.

The highest soil water column occurs in February. This value is close to the field capacity (31.4 vol. %) of the soil in Hartheim. The permanent wilting point was determined to be 11.7 vol. %. This point is often reached during the summer months July and August.

Using the water budget equation we determined monthly values of evapotranspiration E , transpiration E_T and interception E_I . So we measured in addition the following forest hydrological components (Kessler et al., 1988):

P = precipitation above canopy (Fig. 4)

$P_g = P_s + P_t$, with P_g = precipitation on the forest floor, P_s = stem flow, P_t = throughfalling precipitation and precipitation dripping from the canopy (measured by means of a 10-m-long gauge exposed 50 cm above the forest floor)

We give the formulation of the water budget equation used as follows:

$$P = E_s + E_I + E_T + S + \Delta S_w$$

where

$$E = E_s + E_I + E_T; \quad E_I = P - P_g;$$

$$E_T = P_g - E_s - \Delta S_w$$

E_s = evaporation of the soil, E_I = interception, E_T = transpiration, S = percolation and ΔS_w = soil water storage change.

Long-standing pedological investigations gave the result that percolation is negligible in Hartheim (Hädrich, 1979). Before the last thinning (1991/1992) no substantial understory development was observed because of the high shadow rates on the forest floor caused by the canopy. So the assumption of very small amounts of understory transpiration was justified. Therefore the E_T calculations include eventually only very small amounts of this term.

Fig. 14. Mean monthly hydrological conditions at Hartheim site (1974–1991).

Precipitation P and evapotranspiration E show simple yearly patterns with maxima in the early summer and minima in the late winter. The rising slope to the early summer maximum is steeper than the descent to the minimum in winter.

Fig. 15 shows the transpiration E_T and the interception E_I normalized by means of the individual precipitations (E_T/P and E_I/P). This calculation was performed to clarify the influences of the growing forest and the changes of the canopy on the ratio of interception E_I to transpiration E_T related to the time. One can observe in general a trend towards increased specific interception accompanied by simultaneously reduced transpiration. An increasing canopy causes the interception to increase. Thus the

Fig. 15. Normalized interception E_I/P and transpiration E_T/P at Hartheim site from 1981 to 1990.

forest floor yields less precipitation and the specific transpiration must be reduced. The variability of the curves shows, however, that using the calculation of E_T/P and E_1/P ratios, it is not possible to separate completely the influences of the weather noise and the natural changes of the forest on the evapotranspiration processes.

7. Conclusion

Compiling the results of investigations of the heat and water balances of forests, Peck and Mayer (1996) pointed out that it is hardly possible to specify typical values of evapotranspiration E for different tree species. The reason for this dilemma is the fact that it is very difficult to separate out the variations on E produced by:

1. the special conditions of the stand
2. the biometric disposition
3. the local characteristics of the climate

Particularities of the climate can be detected only by means of long time series which are rarely available anyway.

The investigation presented here, based on a time series of 20 years of measurements, tries to detect the influences of stand growth and forest management on the energy and water balance of a pine forest in a climate which is characterized by a widely variable weather. The main difficulty of this analysis was to select the influences of the weather variability from those caused by the natural and man-made changes in the forest ecosystem.

Our main objective was a climatological processing of the time series of measured data. Special emphasis was given to unbroken measuring operations and stable calibrations of the measuring devices. The interpretation of the data showed that it would have been useful to have had a continuous biometrical monitoring of the stand.

Without long time series of measurements of the physical and biological processes it is hardly possible to yield characteristic values for the evapotranspiration E or the net radiation R_n etc. of different forest types. Moreover, we should ask whether we can estimate the problems of 'global change' correctly without the help of long time series of the relevant parameters.

The measurements at the Hartheim site are still going on. We hope to get further results relating to the energy balance and the water balance of our forest by means of climatological methods.

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