LLOYD W. GAY
ROLAND VOGT
ALBRECHT KESSLER

The May-October Energy Budget of a Scots Pine
Plantation at Hartheim, Germany

¹ University of Arizona, Tucson, AZ, USA

² University of Basel, Basel, Switzerland

³ University of Freiburg, Freiburg, Federal Republic of Germany

The May–October Energy Budget of a Scots Pine Plantation at Hartheim, Germany

L. W. Gay¹, R. Vogt², and A. Kessler³

With 9 Figures

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Summary

This paper describes measurements of the Hartheim forest energy budget for the 157-day period of May 11 – Oct. 14, 1992. Data were collected as 30-min means. Energy available to the forest was measured with net radiometers and soil heat flux discs: sensible heat exchange between the canopy and atmosphere was measured with two “One-Propeller Eddy Correlation” (OPEC) systems, and latent energy (evapotranspiration or *ET*) was determined as a residual in the surface energy balance equation. Net radiation, change in thermal storage, and sensible heat flux were verified by independent measurements during the Hartheim Experiment (HartX, May 11–12), and again during the “HartX2” experiment over 20 days late in the summer (Sep. 10–29). Specifically, sensible heat estimates from the two adjacent OPEC sensor sets were in close agreement throughout the summer, and in excellent agreement with measurements of sonic eddy correlation systems in May and September. The eddy correlation/energy balance technique was observed to overestimate occurrence of dew, leading to an underestimate of daily *ET* of about 5%. After taking dew into account, estimates of OPEC *ET* totaled 358 mm over the 5.1-month period, which is in quite good agreement with an *ET* estimate of 328 mm from a hydrologic water balance. An observed decrease in forest *ET* in July and August was clearly associated with low rainfall and increased soil water deficit. The OPEC system required only modest technical supervision, and generated a data yield of 99.5% over the period DOY 144–288. The documented verification and precision of this energy budget appears to be unmatched by any other long-term forest study reported to date.

1. Introduction

The energy budget measurements discussed here begin with the Hartheim Experiment (HartX) on May 11, 1992, and continue through Oct. 14, yielding a set of 30-minute means for the 5.1-month (157 day) period. Use of a simplified eddy correlation/energy balance technique, combined with robust sensors, contributed to the success of this long run. Most forest energy budget studies have concentrated upon detailed measurements over relatively short periods of time. Long-term forest energy budget studies have been undertaken successfully at Thetford (see Stewart, 1988), and to a lesser degree at a number of central European sites as reported by Galoux (1973), Garthe (1985), Kessler et al. (1988), Kiese (1972), Lütze (1969), Schott (1980), Strauss (1969), Tajchman (1967), and Vogt and Jaeger (1990). Details of data quality are not usually given. In contrast, the 1992 forest energy budget at Hartheim is associated with supporting experiments that give confidence in the validity of the measurements. The simplicity, precision, consistency and length of the Hartheim energy budget appears to exceed that of any other long-term forest study reported to date.

2. Measurements and Methods

The energy budget was derived from an eddy correlation/energy balance method in which three of the major forest energy fluxes were measured directly (net exchange of allwave radiation, R_n ; change in thermal storage, G ; and sensible heat flux, H) and the fourth (latent energy flux, LE) was derived as a residual in the surface energy balance. R_n and G can now be routinely measured with a high degree of certainty while using commercial sensors, while the sensible heat flux can be measured readily with eddy correlation techniques. The attraction of the eddy correlation/energy balance method is its simplicity, since no other method at this time offers the possibility of precise, long-term, unattended measurement of the forest energy balance. The uncertainty of this approach derives from lack of direct confirmation of the validity of the residual estimate of latent energy, which is the most difficult of the surface fluxes to measure. Acceptance of the method for this study is based partly on our experience in calibration tests, partly on our confidence in the reliability of the data acquisition systems, and partly on availability here of independent measurements to verify the estimates of the energy fluxes.

The problem of verification is not necessarily solved by simply measuring the two turbulent fluxes H and LE . For 30-min time resolution this is commonly attempted with the Bowen ratio method, or by adding a fast response humidity sensor to the eddy correlation sensor package to obtain direct measurements of LE as well as H . Both the Bowen ratio and the expanded eddy correlation systems require substantial technical attention that render them poor choices for long-term measurements. Also, puzzling discrepancies may exist between forest energy budget estimates based upon mean profiles (either Bowen ratio or aerodynamic models), and those obtained from eddy correlation. Finally, an increasing number of reports (Gay et al., 1996) have confirmed that eddy correlation measurements of H and LE have consistently failed to "close" the energy balance against energy available from R_n and G over a range of surface roughnesses. The theoretically sound, eddy correlation method often fails in practice to detect all of the sensible and latent energy transfer.

The Hartheim energy budget in this analysis is based upon the premise that R_n , G and H are measured correctly, so that closure failures reported elsewhere for the eddy correlation method are attributed solely to the measurement of the latent heat flux. The thrust of this analysis is to draw upon various supporting measurements at the Hartheim site to demonstrate that the three measured fluxes were indeed determined with a high degree of certainty in the summer of 1992. The primary objective is to establish that the derived forest energy balance yields a "good" estimate of the true value of latent energy exchange. The secondary objective is to define and inventory the components of a coniferous forest energy budget through the summer.

2.1 The Measurement Site

The data were obtained in the summer of 1992 from a uniform Scots pine (*Pinus sylvestris*) plantation, located in the southern Rhine Valley at coordinates 47°56' N, 7°37' E at an elevation of 201 m in level terrain 20 km south-west of Freiburg, Germany. Growth at this site has been disappointingly slow from a forestry perspective, but this has contributed to the uniformity of the stand which enhances its attractiveness for meteorological research. The following comments on the site are drawn from the detailed description of Jaeger and Kessler (1996). The measurement towers were located near the center of the 33-year stand which was planted 1961 to approximate dimensions of 5000 m (N-S) by 1200 m. The stand in the vicinity of the towers showed a mean height of 12 m, mean dbh of 11 cm, and mean density of 3925 stems per ha. Estimates of leaf area indices ranged from 2.7 to 3.7. Annual precipitation averages only 667 mm (1951–1980) at this site, and the summer half-year period receives 407 mm, or more than half of the annual total. Average monthly precipitation is reasonably well distributed within the May–October period.

2.2 Experimental Design

The measurements analyzed in this paper were collected by three research groups, operating at several different scales of intensity. The major series of 30-minute mean flux measurements extends over the 5.1-month period May 11–Oct

14, 1992. The University of Arizona's School of Renewable Natural Resources (RNR) measured the turbulent flux of sensible heat (H) between the canopy and atmosphere, and the change of thermal storage in the soil (G_s). The Meteorological Institute of Freiburg (MIF) contributed summer-long measurements of net radiation (R_n) and precipitation (P) reaching the canopy, as well as making available other meteorological variables obtained in its on-going program of research into the radiation and energy budget of Hartheim forest. Special measurement programs at the beginning of the experiment (HartX, May 11–22) and in the late summer (HartX2, Sep. 10–29) were used for verification of the flux measurements. The Meteorology and Climatology Research Laboratory of the Geographical Institute of Basel (MCR) defined reference values of net radiation and thermal storage rates for HartX and for HartX2 (Vogt et al., 1996), and also measured sensible heat fluxes used to verify OPEC sensible heat during HartX2 in September. The Institute of Meteorology and Physics (IMP) of the Agricultural University of Austria, Vienna, participated in measurement of sensible heat fluxes used to verify OPEC sensible heat during HartX in May.

Measurements used in these analyses were obtained on or near two towers located near the center of the forest as described by Jaeger and Kessler (1996). The small tower (15 m high) held the RNR sensible heat flux measurement systems, MIF radiometers (incoming and outgoing all-wave, and incoming and reflected solar radiation), and two rain gages. These sensors operated throughout the summer. In addition, several supplementary net radiometers were mounted on the small tower during the initial, HartX period. The big tower (30 m high) was located 46 m northeast of the small tower: it held temperature, moisture and wind sensors used by MIF to measure profiles throughout the year, and also supported supplementary eddy correlation systems that were operated by MCR during HartX and HartX2.

2.3 Net Radiation

The net radiation (R_n) portion of the available energy was measured by MIF with a Schulze net radiometer at a height of 12.5 m on the small

tower. The net radiation data were prepared by MIF following their normal processing routine as described in detail by Jaeger and Kessler (1980). The polarity of net (and solar) radiation is positive when moving to the surface, and negative when leaving the surface.

2.4 Changes in Thermal Storage

The rate of change in thermal storage (G , W/m²) for the summer energy budget of the Hartheim forest is estimated in this paper as

$$G = G_s + J_H + J_{veg}, \quad (1)$$

where G_s is the rate of change in stored energy within in the soil, J_H is the rate of change of energy stored in the air layer through the canopy, and J_{veg} is the rate of change of energy stored in the forest biomass. This simplified heat storage equation ignores changes in energy associated with changes in vapor content of the air layer. Storage rates in this paper are taken as negative when the substrate gains thermal energy (typical of midday), and positive when the substrate loses thermal energy (typical of night).

In our application of Eq. 1, G_s was measured directly with two pairs of soil heat flux discs buried at 1 cm depth near the base of the small tower, with zero thermal storage rate assumed for the shallow, 1-cm layer of soil above the heat flux discs. Finally, storage in the air (J_H) and in the biomass (J_{veg}) were estimated from a single air temperature sensor at 17 m height. The computations used the "central difference" method described by Stewart (1988) as $J_x = K_x (T_p - T_s)$, where the subscripts p and s specify temperatures in the *previous* and *subsequent* time period, respectively. Various values of K have been used in measurements elsewhere, and overall energy budget results appear to be rather insensitive to the numerical values chosen. In this analysis of J_H , a value of $K_H = 5.73$ W/m²K was used for the 17 m thick air layer, based upon air heat capacity at 20 °C and a 3600 s sample period. For J_{veg} , $K_{veg} = 7$ W/m²K, taking into account an estimate of biomass of 10.1 kg/m² (Jaeger and Kessler, 1996) with an "active fraction" estimated at $f = 0.6$, heat capacity $C_p = 4.19$ J/g·K, and a sample period of 3600 s. Polarities of storage changes in the air and biomass are determined by

$T_p - T_s$ such that J_H and J_{veg} are also negative when the substrate gains energy.

2.5 Turbulent Fluxes

Sensible heat fluxes were evaluated continuously through the summer with two robust eddy correlation systems well-suited for long-term measurements. The sensors were positioned about 3 m apart on the small tower (Gay et al., 1996); system 1 sensors were at a height of 17.10 m, and system 2 sensors were at 17.15 m. These systems correlate fluctuations in vertical wind with fluctuations in air temperature to estimate sensible heat flux with the "eddy correlation" equation first applied by Swinbank (1951). The robustness of the system used in this study derives from the choice of a propeller as the vertical wind sensor, and durable, chromel-constantan thermocouples of 75 microns diameter for measurement of air temperature and its fluctuations. At Hartheim wind and temperature data were sampled at 5 Hz and processed online with a sensitive, battery-powered data logger to yield the needed statistical summaries of 30-min means, standard deviations and covariances. The storage capacity of the data logger was sufficient for many months of operation, but the data were normally downloaded to a portable computer at approximately monthly intervals for subsequent examination and processing.

The robust eddy correlation system used here is similar to the one successfully applied by Amiro and Wuschke (1987) in their 3-month evaluation of summer *ET* in a small, forested catchment. The simplicity of the system derives from its use of a single, vertically-oriented propeller to sense vertical wind fluctuations. This led to the acronym OPEC for "One-Propeller Eddy Correlation". However, advantages of reliability, simplicity, and lower cost that derive from choice of a propeller as an alternative to a sonic anemometer are partially offset by the propeller's decreasing sensitivity to high frequency fluctuations in the turbulence above rough surfaces.

Corrections used to compensate for insensitivity of propellers to higher frequency eddies are described by Blanford and Gay (1992). Their correction has a theoretical and practical basis. It is derived by combining Moore's (1986) descriptions of spectral distributions of turbulence statis-

tics with net system transfer functions. The response characteristics of Gill propellers are well defined from earlier studies (McBean, 1972; Horst, 1973); vertically-oriented propellers consistently show lower sensitivity than sonic anemometers for eddies with frequencies greater than about 0.5 Hz. Power spectra elsewhere (Spittlehouse and Black, 1979; McBean, 1972) show that most of the sensible energy exchanged between forests and the atmosphere occurs during unstable conditions in daytime, at frequencies of less than 0.5 Hz.

Height and stability-dependent corrections for high frequency losses are applied in two steps: (1) the propeller is positioned well above the exchange surface ($z - d > 6$ m) where convective exchange is dominated by larger eddies, and (2) observed OPEC sensible heat is increased either by 10 percent in unstable conditions (typical of daytime), or by 40 percent in stable conditions (as at night). Blanford and Gay (1992) found these procedures brought sensible heat measured by OPEC into excellent agreement with that from sonic eddy correlation systems. The OPEC correction factor is based upon generalized turbulence statistics, so agreement between the OPEC and sonic estimates at the Hartheim forest site will be verified in the following section.

Finally, OPEC sensible heat (HO) is combined with R_n and G to yield OPEC latent energy (LEO) as a residual in the surface energy balance. Polarities for HO and LEO are positive for fluxes into the atmosphere (typical of daytime) and negative for fluxes into the canopy (typical of night).

3. Verifying Fluxes

The components of the Hartheim forest energy budget in the summer of 1992 are verified by comparison of independent flux measurements obtained during HartX and again during HartX2. Some verifications are based upon interpretation of regression analyses of independently measured time series that are serially correlated. We point out that caution must be used in interpreting "goodness of fit" criteria for regression analyses of serially correlated data, even though we accept the usefulness of linear regression procedures for defining relationships. In the comparisons that follow, the linear regression

slope and offset coefficients generally approach ideal values of 1.0 and 0, respectively.

3.1 Verification of Net Radiation

The agreement of the various net radiometers deployed in HartX was considered to be quite good by Vogt et al. (1996), who developed an adjustment in the short- and longwave calibrations that brought all five net radiometers into excellent agreement. The comparisons were among Schulze ($n = 3$), Schenk ($n = 1$) and REBS ($n = 1$) net radiometers. Instruments of the Schulze design performed well during external calibration exercises held previously, and during comparisons with the other net radiometer designs during HartX and so the Schulze design was designated as the HartX standard.

Net radiation measurements used for the energy budget analysis were made throughout the year by MIF with a Schulze ("MIFb", s/n 746), sampled at 30 s intervals and positioned at a height for 12.5 m on the small tower. The MCR Schulze ("MCR", s/n 310 269), positioned at 13.8 m on the small tower, served as a reference during HartX. The primary (R_n) and the reference (R_n') Schulzes in Fig. 1 are in excellent agreement during HartX. The comparisons include $n = 361$ 30-min means during the period DOY 134 to 135.46, and 136.46 to 142.5. The regression equation for this 7.5-day period is $R_n' = 1.01 \cdot R_n - 2$,

Fig. 1. Net radiation verification by two Schulze radiometers in spring of 1992

with $R^2 = 0.9994$ and standard deviation $s = \pm 7$ W/m^2 . The agreement between sensors is excellent, and the variability quite small. This agreement is assumed to continue throughout the experiment, since replications of the net radiation measurements were not available for the HartX2 period in September.

3.2 Verification of Thermal Storage Changes

The rates of thermal storage G obtained from simplified Eq. (1) agree well with independent estimates of reference G' that were determined by more elaborate measurements of Vogt et al. (1996), using procedures of Garthe (1985). These procedures consider changes in water vapor content in the canopy air, and use profiles of temperature and moisture in the soil and in the air as the basis for estimating thermal storage rates in the soil, air and canopy. The polarity of G' (Vogt et al., 1996) has been changed in the following comparisons to be consistent with definitions used in this paper.

Good agreement of G and G' in May and September is evident in the time series plots in Fig. (2A, 2B). The statistical agreement is also quite good. Regression analysis for May shows $G' = 0.97 \cdot G + 1$, with a standard deviation of $s = \pm 11$ W/m^2 and $R^2 = 0.87$. The regression analysis between G and G' in September shows diminished but still satisfactory agreement, with $G' = 0.84 \cdot G - 1$, $s = \pm 11$ W/m^2 and $R^2 = 0.70$. A phase shift between G and G' is evident in September, and if G' is lagged (retarded) by 1.0 hr, the HartX2 regression improves to $G' = 0.91 \cdot G - 1$, with s declining to ± 8 W/m^2 and R^2 increasing to 0.82. Most of the phase shift between the two methods is attributed to the computational differences. All but 8.5 hours of data were available for G vs. G' comparisons during HartX (Fig. 2A), while all thermal storage estimates (960 30-min means) were used during HartX2 (Fig. 2B).

The good agreement between the two independent estimates of thermal storage confirms applicability of the simplified computations during the 5.1 month experiment. In a practical sense, the diurnal range of thermal storage changes at Hartheim is about 10 to 20% of that of net radiation, so that the differences observed here between methods will have negligible effect on latent energy estimates.

Fig. 2. Thermal storage verification by two independent estimates. A) Time series in spring. B) Time series in fall. Primary storage (G), based on heat flux discs and a single air temperature at 17 m, is compared with reference storage (G') which is derived from temperature and moisture profiles in soil and air. Data are 30-min means

3.3 Verification of Sensible Heat Fluxes

Sensible heat flux is a key component in measurements of the Hartheim energy budget. The verification discussion that follows will consider reliability of the OPEC system, agreement of the replicated OPEC sensor sets throughout the summer, and agreement of OPEC estimates with those obtained by sonic eddy correlation systems at the beginning and near the end of the experiment.

3.3.1 Reliability of the OPEC Systems

Two separate sets of OPEC sensors were operated on the small tower for the summer measure-

ment period, and from the conclusion of HartX both sets of sensors were sampled by one data logger. This period of uninterrupted operation extended from DOY 143.78 until 289.00, and included 6971 30-min periods. The only maintenance during this period was a change of anemometer bearings in mid-summer. Sixteen days elapsed between changes in anemometers 1 and 2, so it was possible to test for differences in bearing drag by regression analysis of propeller 1 against 2 for equivalent periods before, during and after the maintenance. No problems were evident.

Results from the two OPEC sensor sets were quite similar over the summer, and sensible heat flux " HO " from OPEC sensor set 1 was selected as the standard. The 30-minute HO values were checked with respect to differences between the two OPEC sensor sets, and 11 data points were flagged for inspection. These were corrected by substituting data from the second sensor set. Thirty-six of the HO values exceeded reasonable range limits, and these were judged to be in error and were corrected by interpolation. Thus over this period of uninterrupted operation, the dual-sensor OPEC system produced 6935 "correct" values out of 6971 30-min samples for a data yield of 99.5%. Many of the 36 out-of-range values were associated with rain, possibly through direct effects on the fine wire thermocouples, or through grounding of the thermocouples against the tower which supported a number of AC power lines. Even so, the OPEC system was really quite unaffected by rain, as only 36 out-of-range values were observed over the summer in which rain occurred during 650 30-min periods.

3.3.2 Comparisons Between OPEC Systems

The agreement between the two sets of sensors can serve as an index to the satisfactory operation of the OPEC systems. Continuous collection of OPEC data began at DOY 134.50, and from this point until the end of measurements at 289.00, the two systems operated concurrently for 7372 30-min periods. These are far too many points for clarity on a scatter plot, and so daily means from DOY 134 through 286 ($n = 152$) are used to illustrate the relation between OPEC sensors in Fig. 3 with OPEC system 1 as the

Fig. 3. Agreement of mean daily sensible heat from two sets of OPEC sensors at Hartheim, May 12-Oct. 12, 1992

Fig. 4. Histogram of sensible heat flux differences ($\delta H = HO1 - HO2$) between the two OPEC sensor sets in daytime

independent variable HO , and OPEC system 2 as the reference variable HO' .

3.3.2.1 OPEC Regression Analysis: A regression analysis of the OPEC daily means shows that $HO' = 1.00 \cdot HO + 1$, with $s = \pm 8 \text{ W/m}^2$ and $R^2 = 0.97$. The standard deviation (s) of the regression is small with respect to the range of H ($-30 < H < 150 \text{ W/m}^2$). Further, the slope of 1.0 and the small offset confirm that the two OPEC systems were in excellent agreement over the season. Regression analysis of 7276 30-min means yields a similar equation ($HO' = 1.00 \cdot HO + 2$, with $s = \pm 19 \text{ W/m}^2$ and $R^2 = 0.98$). The standard deviation has increased in absolute terms, but as a percentage of the range it has declined to about half the value computed for the analysis of daily means.

3.3.2.2 Frequency Analysis of Differences between OPEC Sensors: The absolute value of the differences ($\delta H = HO1 - HO2$) between the 30-min values of the two OPEC systems seldom exceeded 100 W/m^2 , and most of the differences are close to zero. However, the differences δH always approach zero at night when the sensible heat flux is small, unless an unusual measurement error occurs. It is therefore inappropriate to include night values in an examination of δH , and so the histogram of daylight δH values shown in Fig. 4 is based upon daylight δH values.

The table entries are number of occurrences in a population of 3506 30-min, daylight means. About half of the δH values fall within the range $\pm 10 \text{ W/m}^2$ during daylight hours. The criterion used for "daylight" is that $R_n > 0$.

It is also apparent that the absolute value of δH is strongly correlated with magnitude of the sensible heat flux (i.e., the larger the flux the larger the divergence observed between the two OPEC sensors). This is illustrated clearly in the "two-way" distribution of 6822 30-min means (day and night) in Table 1, which uses the magnitude of R_n as an index for δH . Table 1 tabulates the number of occurrences within cells whose dimensions are defined by δH (rows) $= 10 \text{ W/m}^2$ and R_n (columns) $= 50 \text{ W/m}^2$; the rows and columns are defined at the midpoints of the cells. R_n varies from -100 to 800 W/m^2 while δH varies from -100 to 100 W/m^2 . The subtotals of occurrences in each category of R_n are shown at the bottom of Table 1, and range from $n = 5$ to $n = 2506$.

3.3.3 Comparisons Between OPEC and Sonic Eddy Correlation Systems

The agreement of sensible heat flux from the two OPEC sensor sets is reassuringly close throughout the summer, but this provides little information on measurement accuracy. The agreement

Table 1. *The Two-Way Distribution of Occurrences of δH Values with Respect to R_n* . The data consist of $n = 6822$ 30-min means of δH for both daytime and night over the summer of 1992 at Hartheim

Interval Midpoints	Midpoint of net radiation cells (W/m^2)																	
	-75	-25	25	75	125	175	225	275	325	375	425	475	525	575	625	675	725	775
Midpoint of ($\delta H = HO1 - HO2$) cells (W/m^2)	-95	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	1	0
	-85	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	-75	0	0	0	0	0	0	0	0	0	0	0	0	1	4	3	1	0
	-65	0	0	0	0	1	0	0	0	2	0	0	3	1	5	2	1	0
	-55	0	0	0	0	0	1	1	2	0	3	0	2	6	5	3	0	1
	-45	0	0	0	0	0	0	3	4	6	4	5	6	8	8	7	4	1
	-35	0	0	1	0	1	2	5	6	11	11	12	13	22	17	7	4	0
	-25	1	4	2	2	1	8	12	10	24	14	18	17	27	16	20	17	3
	-15	16	32	8	9	27	34	26	29	32	27	22	20	19	25	18	18	9
	-5	522	1664	251	141	98	57	51	43	37	23	25	29	19	15	14	20	11
	5	257	771	273	180	110	71	48	38	32	31	24	17	21	28	22	16	12
	15	11	27	16	40	53	48	41	32	31	22	26	17	22	23	14	13	5
	25	1	3	2	10	22	23	22	21	14	24	16	15	13	10	20	12	1
	35	2	3	1	2	10	17	17	23	13	10	20	10	13	14	11	1	2
	45	0	0	0	0	0	9	8	13	7	10	11	10	7	5	6	7	0
	55	0	1	1	1	0	1	8	3	6	6	9	5	4	6	3	3	0
	65	0	0	0	0	0	0	3	1	4	5	2	2	5	2	5	2	0
	75	0	0	0	0	0	2	1	3	1	0	1	2	3	2	2	1	0
	85	0	1	0	1	0	0	0	1	0	0	1	2	2	2	2	1	1
	95	0	0	0	0	0	0	0	0	1	0	0	0	3	1	1	0	0
$n =$	810	2506	555	386	323	271	240	226	214	191	194	163	179	190	179	135	55	5

between OPEC sensible heat (HO) and reference sensible heat (HS') estimated from sonic anemometer systems can be examined for this purpose. While a variety of surface flux measurements were made during the HartX period in May (Gay et al., 1996), we shall examine in this study only two of several possible OPEC comparisons: (1) OPEC sensible heat flux agreement with an adjacent 1-dimensional SEC system during HartX, and (2) OPEC sensible heat flux agreement with a 3-dimensional SEC system during HartX2. We shall first describe the systems, then visualize OPEC and SEC agreement with time series plots of HO and HS' during the two periods, and then examine regression analyses of HO and HS' .

The 1-d SEC system used for the HartX comparisons was established at 15 m height on the small tower; it was located a little lower than the 17 m level of the OPEC sensors, adjacent to OPEC system 1 and about 3 m from system 2. No corrections were applied to the sensible heat flux estimates obtained from this sonic system. The

1-d SEC system collected data between DOY 134.53 and 143.49, but the period DOY 139.73 to 142.40 are excluded from comparisons because the SEC sensors were operating below the canopy. The HartX comparisons SEC HS and OPEC HO are thus based upon 285 30-min periods of concurrent operation. The 3-d SEC system used for comparisons during HartX2 in September was established by MCR at 22 m height on the big tower (46 m northeast of the OPEC site on the small tower) and operated between DOY 254.60 and 274.00. This SEC system was down occasionally for short periods and during a power outage from 263.08 until 265.60, but 797 30-min periods of concurrent operation are available for comparison with OPEC HO during HartX2. Sensible heat flux measurements from the 3-d SEC system were adjusted for the flow distortion effects of its design, as described by Vogt (1995).

Time series plots of OPEC HO and reference HS' are shown in Fig. 5A for HartX in May (HS' is from 1-d SEC) and Fig. 5B for HartX2 in

Fig. 5. Verification of OPEC sensible heat flux (HO). A) Time series in spring; HS' is from adjacent, 1-dimensional SEC system on the low tower. B) Time series in fall; HS' is from a 3-dimensional SEC system on the high tower. C) Regression analysis for spring. D) Regression analysis for fall. Data are 30-min means from day and night

September (HS' is from 3-d SEC). The two independent measurements of sensible heat flux agree quite well for both periods.

Regression analyses of 30-min mean sensible heat HO versus reference HS' are shown in Fig. (5C, 5D). HS' is from the 1-d SEC in May and the 3-d SEC in September. The May regression shows $HS' = 0.97 \cdot HO + 1$ for $n = 285$ 30-min points, with $s = \pm 24 \text{ W/m}^2$ and $R^2 = 0.977$. Agreement is judged to be excellent, with slope and correlation coefficient close to 1.0 and with the offset and s quite small with respect to the range of sensible heat observations ($-100 < H < 500 \text{ W/m}^2$). In September, the regression shows $HS' = 0.99 \cdot HO + 2 \text{ (W/m}^2\text{)}$, with $s = \pm 26 \text{ W/m}^2$ and $R^2 = 0.88$. The two systems are in close agreement, despite the 46 m distance separating the towers.

The excellent agreement between the OPEC and SEC systems at the beginning and at the end

of the Hartheim Forest measurements, coupled with the agreement of the two OPEC systems throughout the summer, offers convincing evidence for acceptance of the sensible heat estimates in the Hartheim Forest energy budget for 1992. At the very least, the OPEC estimates are seen to be equivalent to those measured with more technologically advanced SEC systems. Further, durability and reliability of the battery-powered OPEC system is confirmed by the 99.5% data yield over five months of measurements.

3.4 Precipitation

Hourly precipitation was measured at Hartheim Forest by MIF with two precipitation gages above the canopy at 16 m on the low tower. The two gages are an ombrometer (drop counter, gage 1) and a Hellmann-type recording gage (analog recorder, gage 2). The 1992 summer

precipitation record is based primarily upon the Hellmann gage, since the ombrometer design tends to underestimate totals during intense storms. Although the Hartheim ombrometer malfunctioned from time to time, it was closely correlated with the Hellmann-type gage during periods of concurrent operation. For days 132–212, 228–259, and 279–288, the ombrometer total was consistently 92% of that recorded by the Hellmann gage (total for these three periods: 189 mm vs. 205 mm). The consistent relationship between the two rain gages on the low tower verifies the validity of the precipitation totals from the Hellmann-type gage at Hartheim during the summer of 1992.

3.4.1 Observed Precipitation Totals

Precipitation observed above the canopy totaled 267 mm over the period May 11–Oct. 14 (DOY 132.00–289.00). No catch deficiency corrections are included in this total since Jaeger (1985) found wind-induced errors in gage catch to be negligible above the Hartheim forest. Rain was recorded on 75 of the 157 days in this period. The distribution of observed precipitation is shown in Fig. 6, with daily totals on the Y-2 axis plotted

Fig. 6. Mean daily energy budget, May 11–Oct. 14, 1992. Symbols: I_0 , extraterrestrial solar radiation at 48°N; K_a , global solar; R_n , net radiation; and P_a is precipitation reaching the canopy. H_{0c} (OPEC sensible heat) and LEO_c (OPEC latent heat) are corrected for dew; P_c is corrected from wetting loss and wind errors. Thermal storage $G = 0$ when $H_{0c} + LEO_c = R_n$.

against day of year. Other information in Fig. 6 will be discussed in detail in the energy budget section below. Precipitation was deficient during the summer of 1992, as observed precipitation totaled only 74% of the normal 360 mm for the period (Jaeger and Kessler, 1996).

3.4.2 Corrections to Precipitation

Results elsewhere with Hellmann-type gages suggest that the observed precipitation is likely affected by small errors associated with “wetting loss” to the gage and wind-induced “catch deficiency” and so corrections were undertaken as follows.

The first correction is a wetting loss adjustment (P_{w1}) which takes into account the unmeasured film of moisture that adheres to the gage. In accord with Sevruk (1982), the average wetting loss for a Hellmann-type gage on a rainy day is taken as $\delta P_{w1} = 0.3$ mm, and so the total wetting loss over a period is $P_{w1} = n \cdot \delta P_{w1}$ where n is the number of rainy days in that period. There were 75 days with rain (including those with only a trace) during the 157-day period of the water balance and so that total adjustment over the season was +22.5 mm.

The adjusted precipitation was then corrected to account for wind-induced catch deficiency, based upon a recent report by Guenter and Graf (1991) who demonstrated that Hellmann-type rain gages caught less in windy conditions than did their special “error-free” reference gage. The minimum catch of 92% was observed when the wind was between 2 and 3 m/s. Thus for the Hartheim Forest water balance, adjusted precipitation above the canopy was corrected for catch deficiency by +6% (corrections applied at Hartheim in earlier periods are discussed by Schott, 1980). Corrected precipitation was computed for each day as $P_c = k (P + P_{w1})$ with $k = 1.06$, and over the summer of 1992 $\Sigma P_c = 308$ mm, or 41 mm more than observed $\Sigma P = 267$ mm.

4. The Forest Energy Budget

After measured, 30-min energy fluxes at the forest canopy (R_n , G , and H_0) were verified against independent measurements as described in Section 3, 30-min means of latent energy (LEO) were computed as the residual term in the surface

energy balance ($R_n + G = HO + LEO$). The basic data set for the forest energy budget thus consists of 7464 30-min means from the period DOY 134.50 to 289.00. This data set contains 36 30-min periods with interpolated turbulent fluxes. Daily (24-hr) means and totals from this set were combined with DOY 132.00–134.5 for which mean daily fluxes were derived by interpolation. These data sets yield mean daily fluxes in W/m^2 for R_n , G , HO and LEO , and totals in mm/day for ETO and P_c over the 157-day period DOY 132.00–289.00.

4.1 Bias in the Turbulent Flux Estimates

Gay et al. (1996) identified a bias in the mean daily (24-hr) estimates of turbulent fluxes obtained by eddy correlation during the 12-day HartX experiment during May 1992. Bias occurs when correctly measured fluxes from turbulent daytime conditions are combined with erroneously low flux estimates from the stable, non-turbulent conditions at night. Recognition of this bias in daily flux totals is important for interpretation of eddy correlation results. For a complete eddy correlation system, the bias causes closure estimates to appear better for 24-hr periods than for either daylight or night periods alone. For the eddy correlation/energy budget method used in this study, the bias appears as an over-estimate of dew in the residual estimate of LE . We call this erroneously high estimate of dew the “phantom dew” error. The energy budget observations at Hartheim reveals that phantom dew occurred throughout the 5.1-month experiment. If erroneous estimates of dew are taken into account, observed LEO from the OPEC system is found to be consistently underestimated by about 6% on a daily basis, while HO is overestimated by an equivalent amount. The development of an approximate correction for phantom dew is summarized below.

4.2 Correcting OPEC Fluxes for Phantom Dew

There is considerable evidence that $|H|$ is underestimated by the eddy correlation method during stable conditions as at night. During the HartX period, Gay et al. (1996) report that nighttime closure of turbulent fluxes from sonic eddy correlation systems at Hartheim was as low as 4% with respect to available energy. Given the flux polar-

ities used in this paper (typically, night $AE < 0$, night $HO < 0$, and $LEO < 0$ indicates dew formation), residual LEO from an OPEC-type system is less than true LEO over 24-hr periods since observed HO is more than true HO . The difference between observed and true LEO is the amount of “phantom dew”. Gay et al. (1996) point out that if no real dew occurs, phantom dew is the total LEO for those periods when $LEO < 0$ and $AE < 0$. In such cases, phantom dew is easily determined from observed data and subtracted from observed ΣLEO (increasing ΣLEO) and added to ΣHO (decreasing HO) to maintain the energy balance over the period. Note that this estimate of “true” LEO is in error by any real dew that forms, since latent energy of condensation will be excluded from analysis of night observations, but the subsequent vaporization will be included in the daytime observations.

If Hartheim LEO were to be corrected for phantom dew with the assumption that no real dew actually occurred, observed OPEC ETO would be increased about 12% over the 5.1-month period, from 338 mm to 378 mm. It is clear such a correction would overestimate ETO by the amount of real dew. There is no simple way to estimate either occurrence of dew or the amount that may form, so the correction for phantom dew at Hartheim can only approximate. Vogt and Jaeger (1990) estimated that dew at Hartheim forest totaled 50 mm over the period August 1985 through December 1986, based upon the time that observed canopy temperatures dropped below the dewpoint of the air. From these results, we assume that 20 mm is a reasonable estimate of the amount of dew that might form over the summer season. This would require the clear night skies, moist air and light winds that favor dew formation (Monteith, 1957) to occur on perhaps 60 nights, with dew to form at a rate of perhaps 0.33 mm/night, for a total of 20 mm. If the 40 mm of phantom dew is reduced by an estimated 20 mm of real dew, the corrected OPEC estimate becomes $ETO_c = 358$ mm over the 5.1-month period, for an increase averaging + 5.9%.

Examination of the data showed that phantom dew occurrence was possible on 154 of the 157 days (i.e., $LEO < 0$ and $AE < 0$). Therefore, for the purpose of defining the seasonal energy

Table 2. *The Energy Budget of the Hartheim Forest During Summer 1992.* The 157-day period extends from May 11 through Oct. 14 (DOY 132 through 288). Turbulent fluxes HO_c and LEO_c are corrected for effects of dew; precipitation sums ΣP_c are corrected for wetting loss and wind-induced catch deficiency

Date	DOY	<i>n</i> days	$K\downarrow$ W/m ²	R_n W/m ²	G W/m ²	HO_c W/m ²	LEO_c W/m ²	ETO_c mm/day	ΣP_c mm
May 11–31	132–152	21	262	167	– 7	80	80	2.82	15
Jun 01–30	153–182	30	240	158	– 6	61	91	3.21	93
Jul 01–31	183–213	31	245	159	– 6	83	70	2.47	52
Aug 01–31	214–244	31	213	127	– 5	79	43	1.52	64
Sep 01–30	245–274	30	155	86	1	29	58	2.05	62
Oct 01–14	275–288	14	74	35	4	6	33	1.16	22
157-day Means:			208	129	– 4	60	65	2.28	
157-day Sums:		157	2815	1744	– 50	820	874	358	308

Note: units for sums are MJ/m² (energy flux densities) and mm (ETO_c and ΣP_c).

budget at Hartheim, a phantom dew correction of +5.9% was applied to LEO for appropriate averaging periods (season, month or day) to obtain our best estimate of LEO_c . HO_c was then obtained from the surface energy balance.

To summarize, the closure of turbulent fluxes at night is a problem for eddy correlation systems. This problem becomes a “phantom dew” error only for simplified systems which derive the latent energy flux as a residual term in the surface energy balance. The close agreement between SEC and OPEC sensible heat fluxes at night confirms that the errors are deficiencies of the eddy correlation method, and not of the sensor system used in the measurements. Closure errors typically are either overlooked or ignored in current practice. The phantom dew error defined here should be recognized here as merely a different form of the closure error, and so the approximate correction used here is only an initial step toward solution of a pervasive problem.

4.3 Energy Budget Results

The daily means for each of the four fluxes are plotted in Fig. 6, along with extra-terrestrial solar (I_o), measured incoming solar radiation ($K\downarrow$) and the corrected daily precipitation total (P_c). The daily forest energy budget over the 5.1 month period can be shown in a single Figure, where HO_c (in a gray shade) and LEO_c fluxes are “stacked bars” while R_n and $K\downarrow$ are time-dependent curves. G (which approaches zero on a daily

basis) is shown indirectly in the Figure; measured G on any given day is the difference between $HO_c + LEO_c$ bars and the R_n curve (i.e., $G = (HO_c + LEO_c) - R_n$).

Daily values ($K\downarrow$, R_n , G , HO_c , and LEO_c in W/m²; ETO_c in mm/day) were averaged within each monthly period and tabulated in Table 2. Table 2 also contains the corrected precipitation total (ΣP_c , in mm) for each averaging period and the number of days in each period. The 157-day total ETO_c from the stand was estimated to be 358 mm after taking dew into account; this exceeded precipitation reaching the canopy ($\Sigma P_c = 308$ mm) by 50 mm. ETO_c and P_c have been closely defined. If they are correct, the 50 mm difference could likely come from extraction of water from the soil mantle. It could also be associated with deep percolation below the active depth of soil which is taken as 1 m at Hartheim. These possibilities will be examined in more detail in the following analysis of the forest water budget.

5. Forest Water Budget

Gravimetric soil moisture data obtained periodically at Hartheim by MIF can be used in a water budget analysis of evapotranspiration (ET_{WB}) as a check on the OPEC estimates of ETO_c for the 5.1-month period in 1992. Soil moisture (SM) analyses have low sensitivity for estimating ET_{WB} , and so averaging periods for SM measurements must extend over many days. Deep drainage and surface runoff are seldom observed at

Table 3. Hartheim 1992 Evapotranspiration Analysis by Water Balance (ET_{WB}) and by OPEC Eddy Correlation Energy Balance (ETO_c). ETO_c estimates take into account the effects of dew

DOY	SM % vol	SM mm	δSM mm	P_c mm	ΣET_{WB} mm	ΣETO_c mm	n day	ET_{WB} mm/day	ETO_c mm/day
132	23.0	92.0							
138	19.7	78.8	-13.3	1.0	14.3	22.0	6	2.4	3.7
153	19.0	76.0	-2.8	26.6	29.4	42.3	15	2.0	2.8
167	17.3	69.2	-6.6	48.0	54.6	46.7	14	3.9	3.3
190	11.2	44.8	-24.6	45.5	70.1	65.7	23	3.0	2.9
213	10.6	42.4	-2.3	37.5	39.8	56.1	23	1.7	2.4
227	9.6	38.4	-4.2	21.0	25.2	21.7	14	1.8	1.6
246	14.8	59.2	20.8	43.3	22.5	31.2	19	1.2	1.6
260	14.4	57.6	-1.4	24.0	25.4	31.2	14	1.8	2.2
279	17.5	70.0	12.4	49.4	37.0	32.1	19	1.9	1.7
288	17.6	70.4	0.4	10.4	10.0	9.1	10	1.0	0.9
Totals:			-21.6	306.7	328.3	358.1	157		

Note: n = number of days in period, and $ET_{WB} = P_c - \delta SM$.

Hartheim and so they will be assumed to equal zero during the relatively dry summer of 1992. Also, precipitation inputs and evaporation losses are both measured above the canopy so the water balance of the forest takes the simple form $ET_{WB} = P_c - \delta SM$. Gravimetric soil moisture data were obtained from MIF for 11 different dates beginning DOY 132 and ending on 288.

Fig. 7. Mean daily water budget. May 11-Oct. 14, 1992. $ET_{WB} = P_c - \delta SM$ when δSM change in soil water during the period, and P_c is precipitation corrected for wetting loss and wind errors. ETO_c from the OPEC system is corrected for dew

Over the entire 5.1 months, $\Sigma P_c = 308$ mm, $\delta SM = 70.4 - 92.0 = -21.6$ mm, and $ET_{WB} = 308 - (-21.6) = 330$ mm.

The water balance can be examined in Table 3 on a period basis, using data obtained by Sturm et al. (1996). Soil moisture data are entered in cols. 2 and 3 of Table 3. One percent SM by volume is equivalent to 4 mm of water at Hartheim, and field capacity is estimated to be 100 mm for the soil layer. Sampling times are assumed to occur at the end of each period, and errors associated with time of sampling within that day are ignored. The change in soil moisture over the period between samples ($\delta SM = SM_t - SM_{t-1}$) is entered in col. 4 of Table 3. Corrected P_c was entered into col. 5.

For each period, water balance ET was calculated as ET_{WB} (mm) = $P_c - \delta SM$ in col. 6, and energy balance ET from the OPEC system was entered as ΣETO_c in col. 7. The number of days (n) in each period is in col. 8. Finally, for each period the daily mean (mm/day) of ET_{WB} and ETO_c were entered in cols. 9 and 10. Over the 157 days, the total water balance $\Sigma ET_{WB} = 328$ mm, which compares quite reasonably with OPEC-produced ET estimates of $\Sigma ETO_c = 358$ mm. The two methods agree within ± 5 percent of their mean of 343 mm.

The water and energy balance estimates of Hartheim Forest ET are plotted in Fig. 7. The period estimates are in reasonable agreement

throughout the summer, and seasonal totals from the two independent analyses are quite close, so the water balance analysis is judged to support acceptance of the accuracy of the OPEC-derived ETO_c values.

6. Discussion

Forest ET averages 2.28 mm/day over the 157-day summer period, and this is a little lower than values reported for Scots pine at Thetford by Dolman et al. (1988). However, Jaeger and Kessler (1996) point out that the limited soil moisture capacity of the shallow soils at Hartheim tends to restrict yearly ET to amounts approximately equal to annual precipitation.

Some quantitative impressions can be drawn from the Hartheim energy balance analysis in Table 2. Sensible heat slightly exceeded latent energy, as the 157-day Bowen ratio of HO_c/LEO_c was 1.07. Monthly Bowen ratios varied during the warmer summer months from 0.67 in June when the partitioning process favored latent heat, up to 1.84 for August when the partitioning process favored sensible heat (i.e., soil moisture became limiting). These Bowen ratios are in reasonable agreement with long-term means reported for Hartheim by Jaeger and Kessler (1996) as 0.74 in June and 1.57 in August.

6.1 Energy Balance under Clear Skies

The variability evident in the plot of the Hartheim Forest energy balance in Fig. 6 conveys an impression of variable energy inputs and frequent occurrence of rain. In contrast, the forest energy balance is typically quite stable during periods of clear skies with fine weather. Clear sky conditions are easily identified from solar radiation observations, and 47 "clear" days for the period DOY 132–288 were selected for closer examination. The mean daily energy balance components (K_d , R_n , G , HO_c and LEO_c) are plotted against DOY in Fig. 8; "lowless smoothed" curves are drawn through the data points to illustrate the seasonal behaviour of the energy budget components at the Hartheim Forest site when clear skies prevail.

The smoothed curves show that partition of available energy ($R_n + G$) into HO_c and LEO_c is approximately equal during the spring and fall when soil water content at the site is high, but there is noticeable divergence between declining

Fig. 8. Mean daily energy budget on clear days ($n = 47$) in summer 1992. Energy flux density curves are smoothed, and soil moisture deficit (Y2 axis, mm) is estimated as $SM - 100$

LEO_c and increasing HO_c during the warm, rather dry period of July and August. Thus transpiration from the forest diminishes as water available in the soil decreases. The timing of this effect is shown clearly in Fig. 8 with respect to the soil moisture deficit at Hartheim. Soil moisture deficit in Fig. 8 was calculated from soil moisture in col. 3 of Table 3, using a field capacity value of 100 mm water content. Note that the actual value chosen for field capacity is of minor importance in Fig. 8, as it merely sets the scale of the deficit plot. The soil moisture analysis is rather crude (averaging periods range from 6 to 23 days in length), but the midsummer divergence between HO_c and LEO_c at Hartheim is in good agreement with soil moisture deficit.

6.2 Flux Accumulation through the Summer

The accumulated daily precipitation and energy flux densities at Hartheim are plotted in Fig. 9 for the 1992 summer season. The accumulation curves of the energy fluxes increase smoothly and steadily throughout the summer. The day-to-day variability that dominates Fig. 6 is of minor importance on a seasonal basis. The accumulation curves permit the energy and water balance of the stand to be visualized at any point in time. In particular, accumulation curves for LEO_c and

Fig. 9. The accumulation of energy and precipitation at Hartheim forest during the summer of 1992

P_c remain closely associated through the summer, since LEO_c can rise above P_c only to the extent that moisture is extracted from the soil mantle, and the field capacity of the shallow soil at Hartheim is only about 100 mm.

7. Conclusions

The Hartheim forest is a large, uniform site that is exceptionally well suited for energy budget studies. A substantial support structure and data base have developed at Hartheim as a result of the MIF program of forest climatology research over the past two decades. The regional climate tends toward the dry side, the canopy is somewhat sparse, and the soils are shallow with limited capacity to store water. These factors combined with physiological characteristics of Scots pine tend to favor partitioning of available energy into convection rather than into vaporization.

These site characteristics match well with requirements of the OPEC system, and two sets of OPEC sensors agreed extremely well throughout the summer. The battery-powered system and robust eddy correlation sensors proved to be highly reliable, with a yield of acceptable 30-min mean data of 99.5%. The system data logger would occasionally over-range during rainy periods, either as a result of direct thermal effects of rain on the exposed, fine wire thermocouples, or

perhaps because of inadvertent grounding of thermocouples to the tower which contained AC power lines for other equipment. However, this problem occurred on only a small percentage of the rainy days. Redundancy in flux measurements made it possible to independently verify net radiation, thermal storage rate and sensible heat flux for 12 days at the beginning of the measurements, and for 20 days near the end of the summer. Agreement between OPEC measurements and independent references was excellent. Further, OPEC ETO_c corrected for effects of dew maintained reasonable agreement with water balance estimates of ET . Total ET from the two methods agreed within 5% of their mean for the 157-day summer period.

Hartheim precipitation in 1992 was about 75% of normal. Observed precipitation $P = 267$ mm (157 days) was adjusted to account for wetting loss at the gage (0.3 mm per rainy day), and then adjusted P was corrected by +6% for wind-related catch deficiencies to yield $P_c = 308$ mm. The corrected P_c of 308 mm compares with the mean ET of 343 mm; most of the excess of ET over P_c was extracted from soil moisture storage.

An energy budget analysis of days with clear skies demonstrated the substantial role that moisture conditions exert over forest ET . For all days in June when soil moisture was high, $LE/H = 1.3$; for all days in August when soil moisture was low, $LE/H = 0.5$. The LE/H ratio increased again in September, to 1.7, as damp, rainy weather returned. The direct relationship between soil moisture and ET is the basis for modeling the forest energy budget. Our experiment clearly and unequivocally demonstrates this control. Usefulness of the data set described here is enhanced by the uniform characteristics of the Hartheim forest, by the demonstrated and documented performance of the OPEC sensors, by the variety and quality of supporting measurements, and by MIF's long history of radiation, heat and water budgets at the Hartheim site.

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Author's addresses: L. W. Gay, School of Renewable Natural Resources, 325 Biological Sciences East Bldg., University of Arizona, Tucson, AZ 85721, U.S.A.; R. Vogt, University of Basel, Basel, Switzerland; A. Kessler, University of Freiburg, Freiburg, Federal Republic of Germany.