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Abstract

A hydrological monitoring programme is performed in a Douglas fir stand. The programme is part of the ACIFORN project which aims at assessing the influence of air pollution on tree vitality. During one growing season, rainfall and throughfall, canopy water storage, soil water content, sapflow, transpiration of individual branches and stand average evapo-transpiration were measured on a continuous basis to quantify the different water flows through the forest ecosystem. The forest site and the experiments are described. The goals of the project are to obtain experimental information to develop and test models and to facilitate interpretation of other measurements in the ACIFORN context with emphasis on: canopy water storage dynamics and its relation to wet forest evaporation; the relation between stomatal resistance and environmental factors, both on branch level and on stand level; soil water uptake in relation to soil conditions and forest transpiration; soil water availability in relation to throughfall patterns and the spatial distribution of soil properties. In a number of preliminary analyses it is shown that the data-set has the potential to meet these goals.

Introduction

As part of the project "ACIdification of FORest in the Netherlands", an interdisciplinary research programme on the influence of air pollution on tree vitality (Vermetten et al.,1986, Evers et al.,1987), a hydrological programme is carried out to assess the water cycle of a Douglas fir stand.

Traditionally hydrology of forests has been studied both for forestry and for water management purposes. More recently it has been recognized that knowledge of forest water cycles is of interest in other research fields too, such as the study of air pollution effects on ecosystems and climate modelling. Deposition processes of air pollution components are likely to be influenced by canopy wetness. For dry canopies stomatal opening may play an important role in the deposition processes of at least some components. Root growth and soil chemical and biological properties are not only related to stand average soil water dynamics, but as a result of the non-linearity in response, they are also influenced by the spatial variability of soil water dynamics. Evapo-transpiration forms a major component in the energy balance of the earth surface. Knowledge of the dependence of forest evaporation and transpiration on external factors are therefore of considerable importance in climate studies.

The ACIFORN hydrological monitoring programme provides experimental information for developing and testing models and facilitating interpretation of other measurements within the ACIFORN context. Focus is on four processes, which are: (1) canopy water storage dynamics and its relation to wet forest evaporation, (2) the relation between stomatal resistance and environmental factors, both on branch and on stand level, (3) soil water uptake in relation to soil conditions and forest transpiration, (4) soil water availability in relation to throughfall patterns and the spatial distribution of soil properties.

The experimental set-up of a forest hydrological programme is dictated to a large extent by the different ways water finds its way through the ecosystem. All the different measurement techniques give information about water flows on different time scales and spatial scales. For example, soil moisture varies over periods of days during dry conditions, while the soil properties vary considerably over the forest stand and on much smaller spatial scales. Canopy water storage, on the other hand, varies within minutes during a rain storm. With this in mind, the different experiments have been designed to give stand average values.

Monitoring has been started in 1986. However over the years an increasing amount of techniques has been implemented at the research location which has culminated in an extensive set of measurements during the growing season of 1989. Here we will describe the research location and outline the experimental set-up and the measurements made in 1989. A number of analyses will be presented, illuminating the potential of the dataset.

Site Description

The ACIFORN monitoring research site is located at the West side of the Veluwe in an extensive forested area in the centre of the Netherlands. Height is 50 m above sea level. The local climate is moderate maritime with rain throughout the year. The annual precipitation amounts to 800 mm. Mean January temperature is 1.5 °C and mean July temperature is 17.0 °C.

The forest site is part of an extensive forest area which has its nearest border to the east at a distance of 1.5 km, neighbouring a heather area. In the other directions the forest extends over at least 4 km. Within this area the topography is slightly undulating with height variations of 5 to 10 m. The forest consists of small stands of 2-3 ha of different species such as Larch, Spruce, Scots pine, Beech and Douglas fir. The stands show different average tree heights resulting in steps of typically a few meters between the bordering stands. The research forest stand covers 2.5 ha of Douglas fir (*Pseudotsuga menziesii*, Franco L.) planted in 1962. Tree height ranges from 16 to 20 m. The tree density is 785 trees/ha. Leaf area index is approximately 10 but varies throughout the year. The average diameter at breast height is 0.23 m. The stand is very closed at the crown level and almost no open spaces are observed between the trees. Consequently little light enters the forest interior and no understory vegetation is present. More details about stand architecture and crown architecture are presented by Evers et al. (1991).

The forest floor consists of a litter and fermentation layer with a thickness of 0.04 to 0.08 m. The site is located on an ice pushed ridge, where different textures are found within short distances. The soil can be classified as a Typic Dystrochrept on sandy loam and loamy sand textured river sediments. Vertically, texture changes from fine sandy loam in the top layer to fine sand at 1 m depth. Tiktak et al. (1988) give a more detailed description. The ground water table is at 40 m and thus capillary rise to the root zone can be ignored. Measurements of the vertical distribution of root density show that the forest has a low root density which varies strongly in response to soil drought (Olsthoorn, 1991; Olsthoorn and Tiktak, 1991). Most roots are found in the upper 0.5 m of the profile.

Hydrological Measurements

The experimental set-up is based on the different pathways of water through the forest ecosystem. Figure 1 represents this water cycle in a simplified way. Starting with precipitation, a fraction is intercepted and stored in the canopy, subsequently evaporated back into the free-atmosphere. The other part arrives as throughfall at the forest floor. Stemflow is found to be negligible. The largest part of the throughfall penetrates the soil layer were it may drain to deeper soil layers or where it may be taken up by the root system of trees. Run-off is not important in this forest stand. Sapflow is transported to the tree crowns where it is transpirated into the free-atmosphere mainly through stomata. The instruments that measure these different water fluxes are described in some detail below.

Rain and throughfall

Rain is measured at 6 m above the canopy with two automatic gauges with a time resolution of 2½ minutes. Rain is also measured at a clearing 1.5 km North of the research location. Throughfall is measured by two clusters of nineteen and thirty-six rain gauges respectively, to allow the calculation of a reliable stand average.

Canopy water storage

To determine the vertical distribution and the temporal dynamics of canopy water storage, a micro-wave transmission device is used (Bouten et al. 1991). The attenuation of a 10.26 Ghz micro-wave signal is measured over a path of 15 m which intersects a representative amount of tree branches and needles. The instrument is designed to make scans every 5 minutes with a vertical resolution of 8 mm. Therefore, the micro wave transmitter and receiver are mounted in hoists at the outside of two towers standing 15 m apart. Both hoists are driven by one central motor thus ensuring a perfect parallel displacement of the transmitter and the receiver. Calibration is based on rain and throughfall measurements during ideal conditions (Calder, 1991; Bouten and Bosveld, 1991).

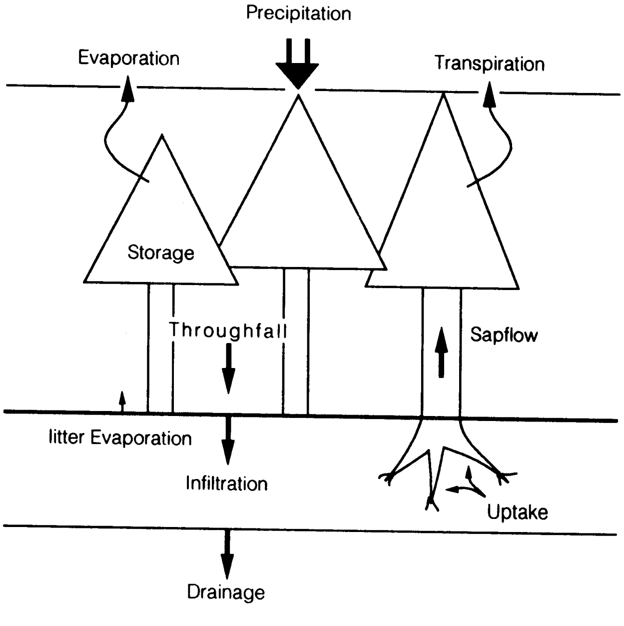

Figure 1 The main water flows through the forest ecosystem.

Soil water content

Since the soil is rather inhomogeneous in the horizontal direction, special attention is given to measure soil water variability. Soil water potential is measured twice a day with an automatic scanning tensiometer system (Burt, 1978). Water content is measured with Time Domain Reflectometry (TDR) (Topp et al., 1980; Heimovaara and Bouten, 1990) in the top soil and with neutron scattering in the subsoil (Gardner and Kirkham, 1952). Ninety-two TDR sensors of 50 cm long and fifty-seven sensors of 70 cm long have been installed vertically to obtain reliable mean water contents of the most intensely rooted soil zone. In prolonged dry periods, TDR measurements are carried out with a varying frequency ranging from three measurements per day to one measurement in two days. Neutron probe measurements are carried out at least once every week. The measurements are obtained in three access tubes to a depth of 2.35 m. A detailed description of the soil hydrological monitoring programme is given in Tiktak and Bouten (1990).

Sap flow measurements

Sapflow velocities can be used to estimate the dynamics of tree transpiration rates. Xylem sap flow velocity of trees are measured by means of the heat pulse velocity technique (HPV) (Marshal, 1985). The HPV technique is based on the advection of a heat pulse. To this purpose a 10 Joules heat pulse is generated in a heating wire, wrapped around a thin pin which is horizontally driven into the sapwood of a tree. Two Pt100 sensors at about 10 mm, one in upflow and one in downflow direction, are used to measure the time lag of the heat pulse. From these measurements the contribution of heat diffusion and convection to the heat pulse velocity can be calculated. Measurements are taken every hour at 12 trees grouped in 4 trees at 3 sites within the forest stand. For each tree two sensors are used, one situated on the north side and one on the south side of the tree at breast height. A more detailed description is given in Noppert et al. (1991).

An advantage of this technique is the relative ease with which continuous timeseries can be obtained over periods of seasons. However, transformation of sapflow velocities to stand average water fluxes is not trivial. Emboly or non uniformness of tracheids and difference in light exposure of individual trees may cause large variation in measured sapflow velocities. Moreover, the detection limit varies from sensor to sensor.

Branch transpiration chambers

To obtain data on water vapour exchange of trees, a branch chamber has been designed that can enclose up to 12 cm of a branch (Steingröver et al., 1991). The branch chamber consists of two units: a transparent unit on the upper side which encloses a branch part and a non-transparent unit which regulates the temperature inside the branch chamber. The chambers are supplied with ambient air sucked from the middle of the canopy. Although the chambers were used for measuring CO_2 exchange as well, we concentrate here on the H_2O exchange measurements. The air is conditioned to the temperature measured outside the chamber while the relative humidity is conditioned to 90% in winter and 75% in summer. The water vapour concentration of the air flow into and coming out of the branch chamber is measured with infrared gas analyzers. Sixteen chambers were operated simultaneously and distributed evenly over three canopy depth i.e. sun,mid and shadow level. Accompanying these measurements photo active radiation (PAR) was measured next to each branch chamber.

Evapo-transpiration

To measure the water vapour flux that leaves the forest by evapo-transpiration, three micro-meteorological methods are used. Firstly, eddy correlation measurements are performed at 30 m above the forest floor.

Turbulent water vapour density fluctuations are measured with a fast response Ly-α hygrometer (Buck,1976), while the turbulent vertical wind speed fluctuations are measured with a sonic anemometer. Covariances are calculated each 10 minutes. A correction for temperature on the water vapour density measurements is performed (Webb, 1981). The Ly-α hygrometer is only operated during fair weather conditions. Secondly, water vapour fluxes were derived from dry- and wet bulb temperature profile measurements on the basis of modified flux-gradient relations (Bosveld, 1991). Thirdly, evapo-transpiration is obtained from the residual of the energy balance.

The last two techniques are operated on a continuous basis, but they are less accurate than the eddy correlation technique. The profile measurements suffer from the small vertical gradients of dry- and wet bulb temperature in the highly turbulent airflow over the forest, while the energy balance method needs an estimate of the storage of heat into the biomass and soil. Interpretation problems arise for the micro-meteorological methods because they are influenced by an upwind source area that extends over the boundary of the forest stand. Schmid and Oke (1990) give a quantitative description of the source area from which the flux resides, at least for neutral and unstable atmospheric conditions.

Additional measurements

Additional measurements are performed to document factors that may influence the water cycle of the forest. Those measurements include soil characteristics (Tiktak and Bouten, 1990), root growth (Olsthoorn, 1991), needle dynamics and crown architecture (Jans et al., 1990). Global radiation, net radiation and canopy radiation temperature are measured. Also temperatures in the soil and dry bulb and wet bulb temperature at 4 m above the forest floor are measured. Besides the dry bulb and wet bulb temperature profile measurements, wind speeds are measured at four levels above the forest together with wind direction. Eddy correlation heat and momentum fluxes are derived from a sonic anemometer-thermometer system.

Preliminary results

In this chapter some preliminary analysis are presented that illuminate the potential of the data set.

The energy balance

To test the reliability of the measurements and to see whether advection effects are important for this specific location we analyse the energy balance.
The energy balance is given by:

$$Q_{net} = H + \lambda E + G$$

where:

Q_{net}	Net radiation
H	Sensible heat flux
λE	Latent heat flux
G	Soil and biomass heatflux

Here we use daily average values so the heat storage term G can be neglected. The heat fluxes are based on eddy correlation measurements. According to Price and Black (1989), energy used for carbon fixation is small, so this term is neglected too.

Figure 2 shows the energy balance for all dry days when the appropriate measurements were available. It shows a systematic deviation of circa 10 W/m^2 on many days. This deviation can result from calibration uncertainties or from the inhomogeneity of the net radiation field over the forest. However, on some days much larger deviations occur. These deviations always have the same sign and are probably related to advection effects from specific wind directions for which in the upwind direction more open forest allows the sunlight to penetrate down to the forest floor.

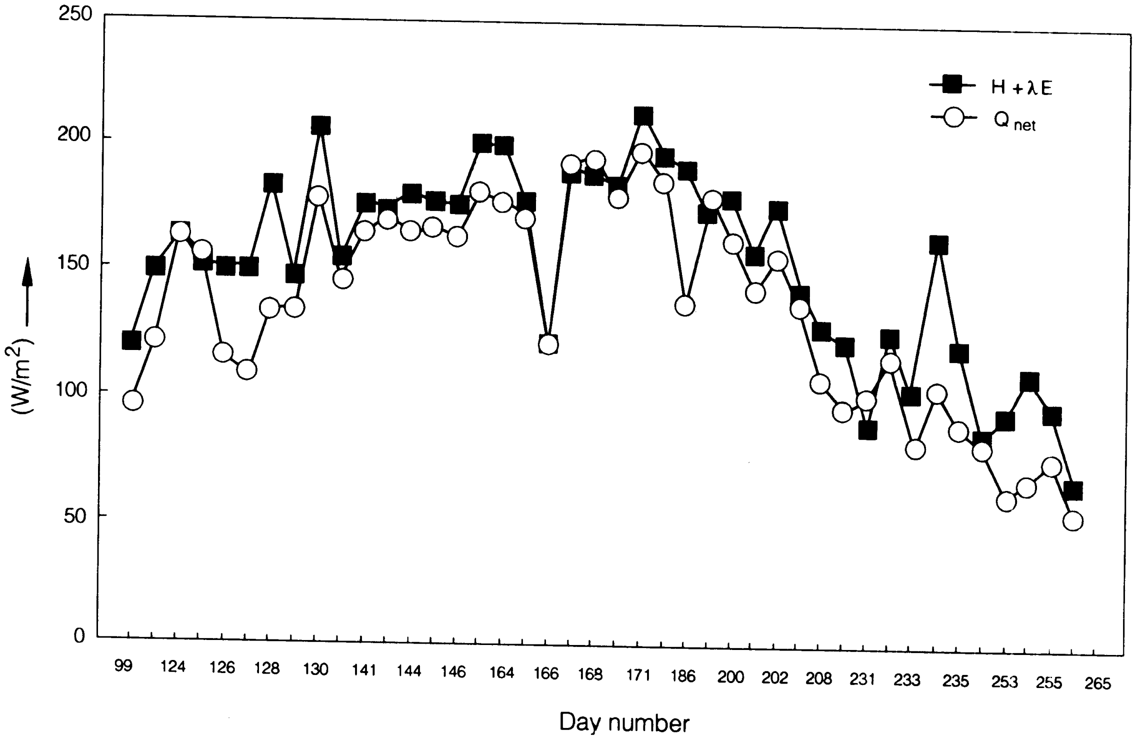

Figure 2 The energy balance for 43 dry days (not consequetive). Daily averaged total turbulent heat flux (eddy correlation) and daily averaged net-radiation.

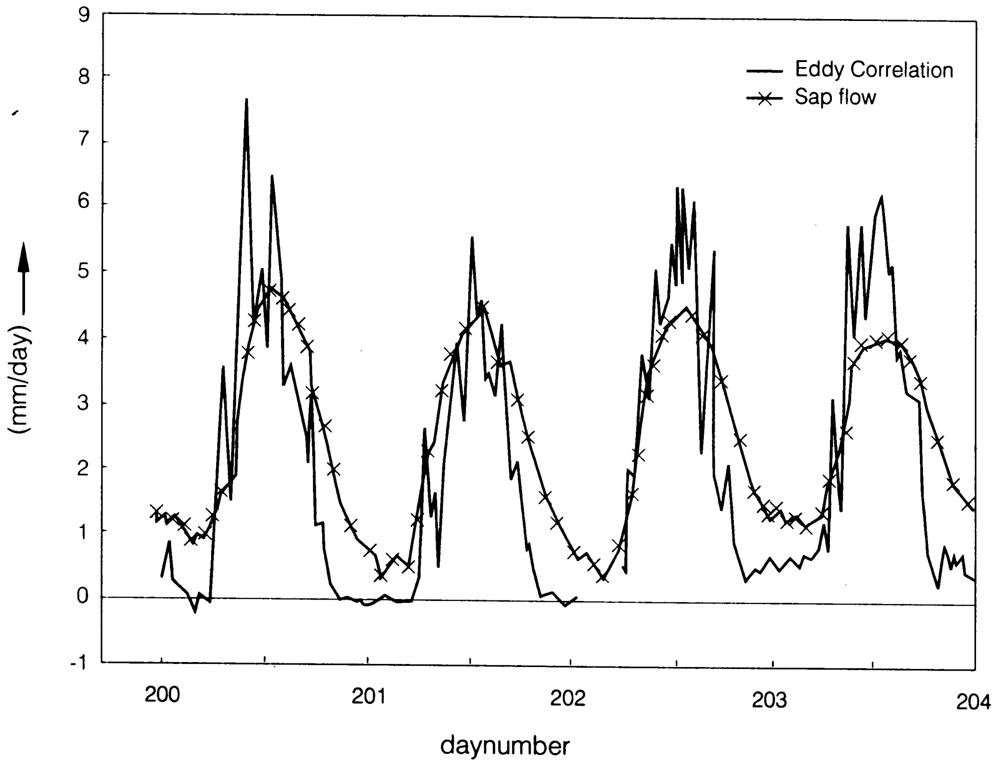

Figure 3 Hourly values of sapflow and eddy correlation transpiration for four days.

Soil water uptake versus transpiration

For the comparison of transpiration estimates from soil water balance calculations and from eddy correlation measurements, 23 measuring periods with no rain and with negligible drainage have been selected. The lengths of these periods range from 1 to 2.5 days. Water uptake is derived from the difference in successive TDR-measurements. Transpiration rates are estimated from eddy correlation water vapour fluxes integrated over time. The summed amount over all the periods is 85.1 mm for soil water and 78.0 mm for eddy correlation, indicating a fairly good agreement between these two different measuring methods.

Sapflux versus eddy correlation

Figure 3 shows a time series of sapflow and eddy correlation measurements for four consecutive days in July. Clear differences are observed in the dynamics of the two quantities. Differences are observed earlier by Granier et al. (1990) and by Schulze et al. (1985). These differences are ascribed to the water buffering capacity of the crown. Both these reported measurements and models (Kowalik et al., 1988), show a time lag of up to three hours between the daily maximum of tree transpiration and that of the sapflow.

In our measurements no time lag is found for the daily maximum. The sapflow follows the transpiration in the early morning and both show a maximum shortly after noon, whereas in the late afternoon and at night sapflow lags behind tree transpiration. A more complex model than single capacitance models will be needed to describe these sapflow dynamics.

Bulk stomatal resistance

Bulk stomatal resistance models for forests are derived in several studies (e.g. Tan and Black, 1976; Stewart, 1988). All these studies suggest that stomatal resistance is influenced by incoming short wave radiation, water vapour deficit and soil water content (Black, 1979). Since short wave radiation and water vapour deficit are strongly correlated, it is difficult to separate the influence of these factors.

Bulk stomatal resistances are derived from hourly sapflow measurements and additional meteorological measurements, following the Penman-Monteith equation (Monteith, 1965). To detect the influence of water vapour deficit and soil water content on stomatal conductance, two periods are selected. The first from daynumber 180 to 196, a period just after shoot growth but with sufficient soil water available. The second from daynumber 199 to 204, a period when the soil is much drier. For both periods data between 10 and 14 hour GMT are used. Figure 4 shows calculated stomatal conductance as a function of water vapour deficit. For both periods a hyperbolic response on water vapour deficit is found. The dry-soil period clearly shows lower conductances.

Evaporation of wet canopy

Evaporation of wet forest is a nice example of the canopy interaction between the local and the regional scale (Morton, 1984). Wet canopy evaporation can be larger than the available energy (Stewart, 1977). This means that energy is imported from elsewhere. During such conditions high rates of forest evaporation can be maintained. If the forest site was of infinite extent and homogeneous, then it would more likely develop a stable boundary layer, which after some time would become saturated with moisture and thus decrease the evaporation rate.

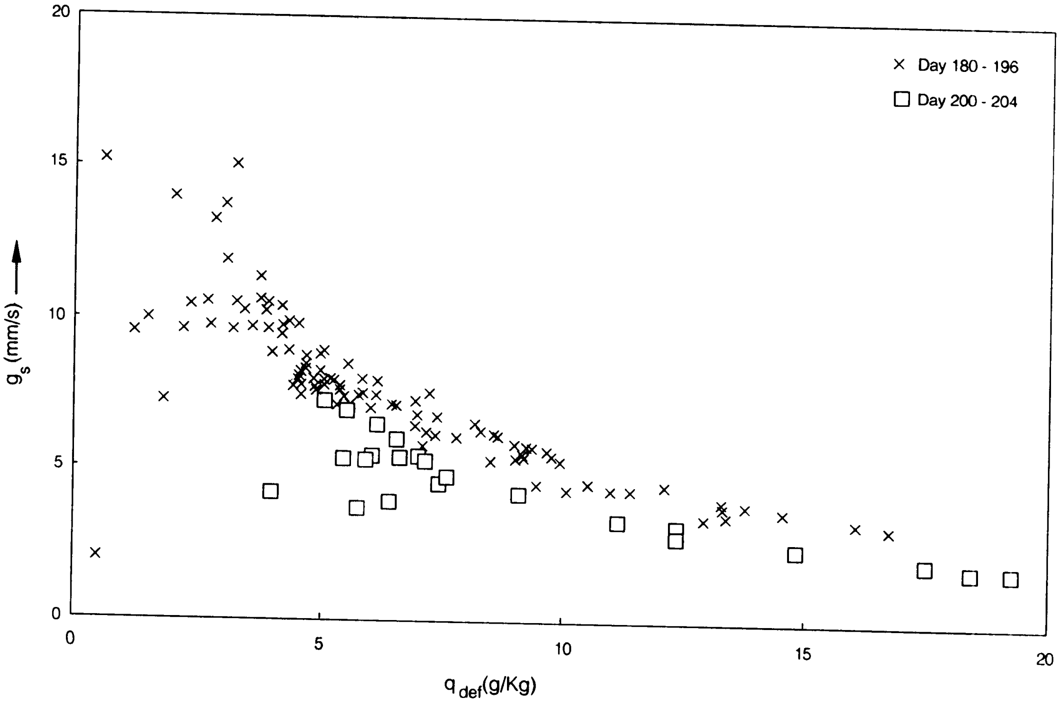

Figure 4 Bulk stomatal conductance (g_s) as a function of water vapour deficit (q_{def}) for a wet soil period (daynr 180-196) and a drying soil period (daynr 200-204), based on sapflow measurements.

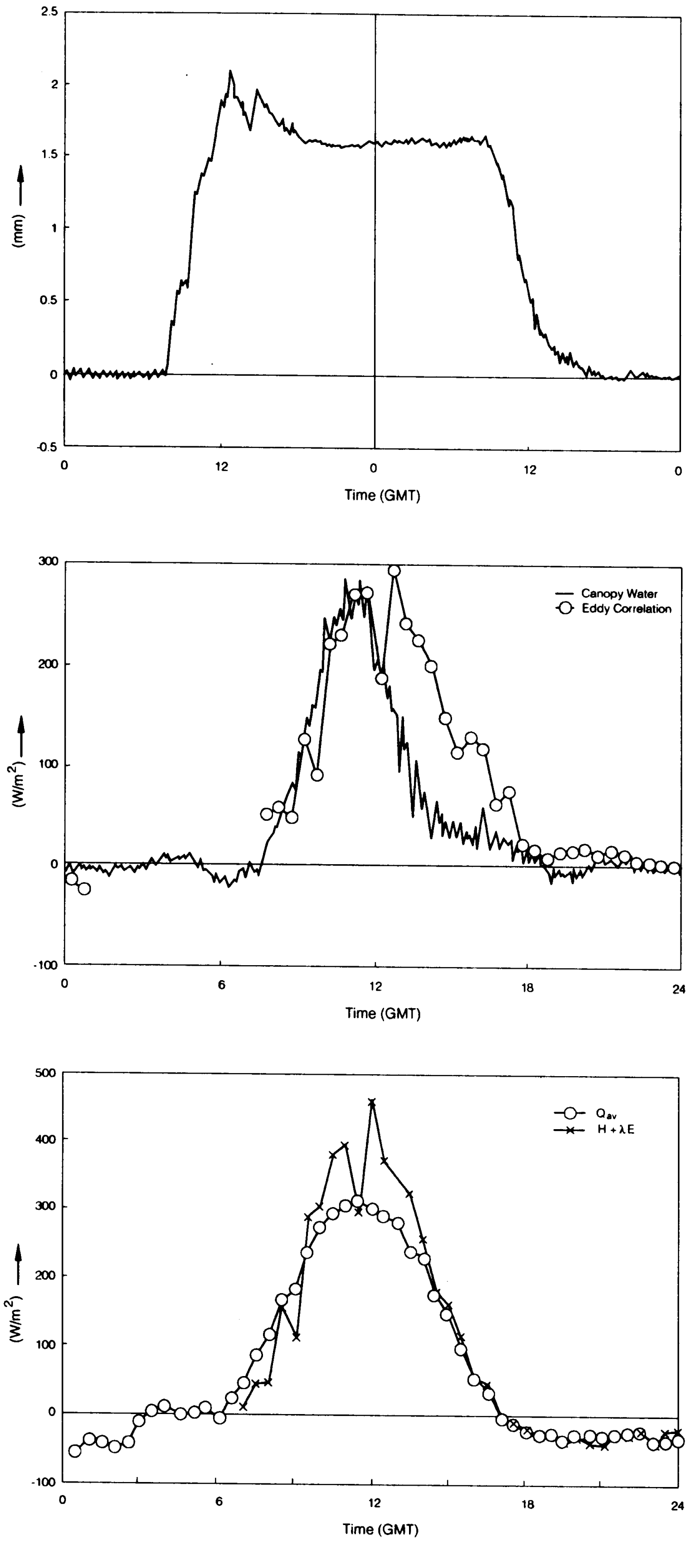

Figure 5 Evaporation during a rain episode (19-20 Sep.1989). a) Canopy water storage (19-20 Sep.). b) Canopy water storage rate of change and eddy correlation evaporation above the forest (20 Sep.). c) Net radiation corrected for biomass and soil heat flux (Q_{av}) and total eddy correlation heatflux (H+λE) (20 Sep.)

Figure 5a shows the canopy water storage, measured with micro-wave transmission, before, during and after a rain episode (19 and 20 September 1989). Figure 5b shows the evaporation measured with the eddy correlation technique and evaporation of the intercepted water derived from the time rate of change of the canopy water storage. Here the eddy correlation water vapour flux is corrected for the rate of change of the storage of water vapour in the air colomn below the instrument. Before noon both methods give nearly equal evaporation rates. Later, when the evaporation from canopy water decreases the eddy correlation technique gives higher values, presumably due to the onset of forest transpiration when the canopy is only partially wet. Figure 5c shows the energy balance where Q_{av} is the available energy derived from the net radiation and corrected for biomass and soil heat flux. It is observed that an amount of heat is missing in the energy balance. Probably this missing energy is advected into the forest from drier regions in the surrounding area.

Branch chamber transpiration and PAR

The upscaling of evaporation measurements from the branch level to the stand level is not trivial. Finnigan and Raupach (1987) show that the bulk stomatal conductance is not a simple summation over the conductances of the individual needles or leaves.

Here we limit ourselves to the branch level. Figure 6 shows the measured transpiration rate of one branch chamber for a cloudless day together with the measured PAR just outside the branch chamber. Due to tree shading PAR is very low in the morning but increases sharply when the chamber comes into the sunlight. It is observed that the transpiration rate increases in response.

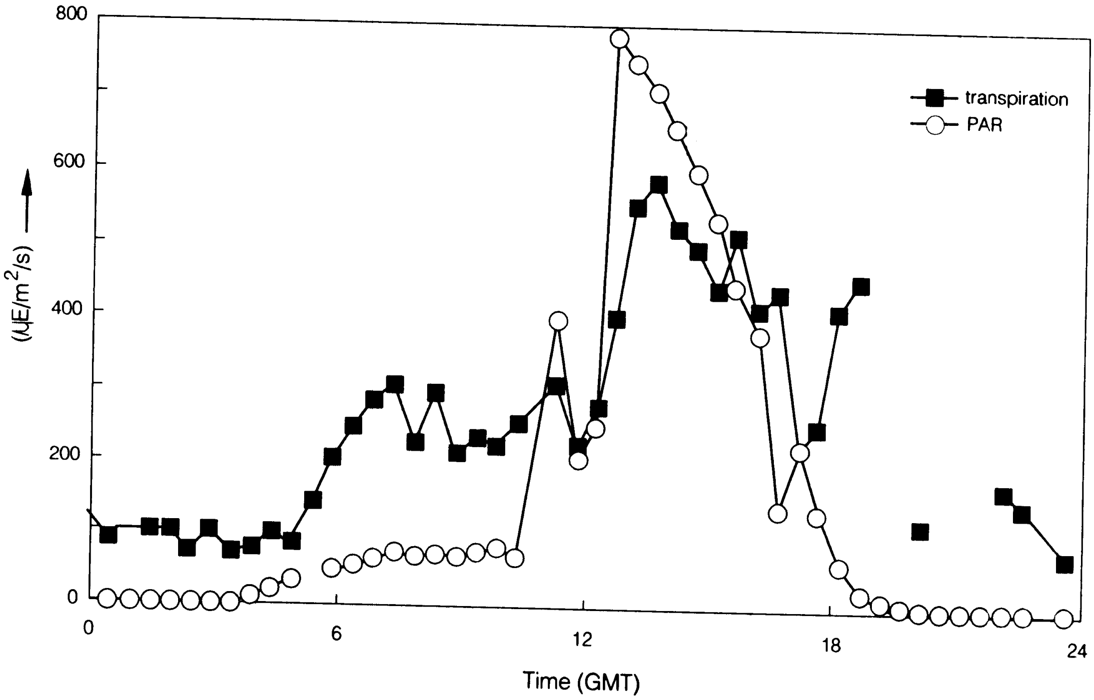

Figure 6 PAR and branch chamber transpiration for one day in 1989. Units are in flux density of photons and molecules respectively, where the numbers of photons and molecules are expressed in μ-Einstein.

Conclusions

A hydrological programme to assess the water cycle within a Douglas fir forest is performed in the context of research on air pollution effects on forests. A number of very different techniques are used to quantify flow rates of water through the forest ecosystem. Since the flow rates vary on different spatial and time scales, special attention is given to arrive at reliable estimates of stand average values.

An analysis of the energy balance on a daily averaged basis shows some days with considerable excess energy coming into the forest. Probably this energy is related to a different radiation condition of the upwind terrain. A comparison of soil water uptake and transpiration measurements above the forest shows a difference of 10% in the total amount of water. A comparison of the dynamics of sapflow and transpiration measurements shows that both quantities peak just after noon. This is in contrast with earlier findings where sapflow always lags transpiration. From a classification of the transpiration data it is shown that both water vapour deficit and soil water content have a clear effect on bulk stomatal resistance. It is shown that canopy water storage can be measured with high time resolution and compares well with evaporation measurements above the forest. Detailed information is obtained on transpiration at the branch level. It can be concluded that the combination of different measuring techniques gives valuable information to develop and test models of the forest water cycle and may facilitate a better interpretation of air pollution measurements in relation to tree vitality.

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